PB85-213429

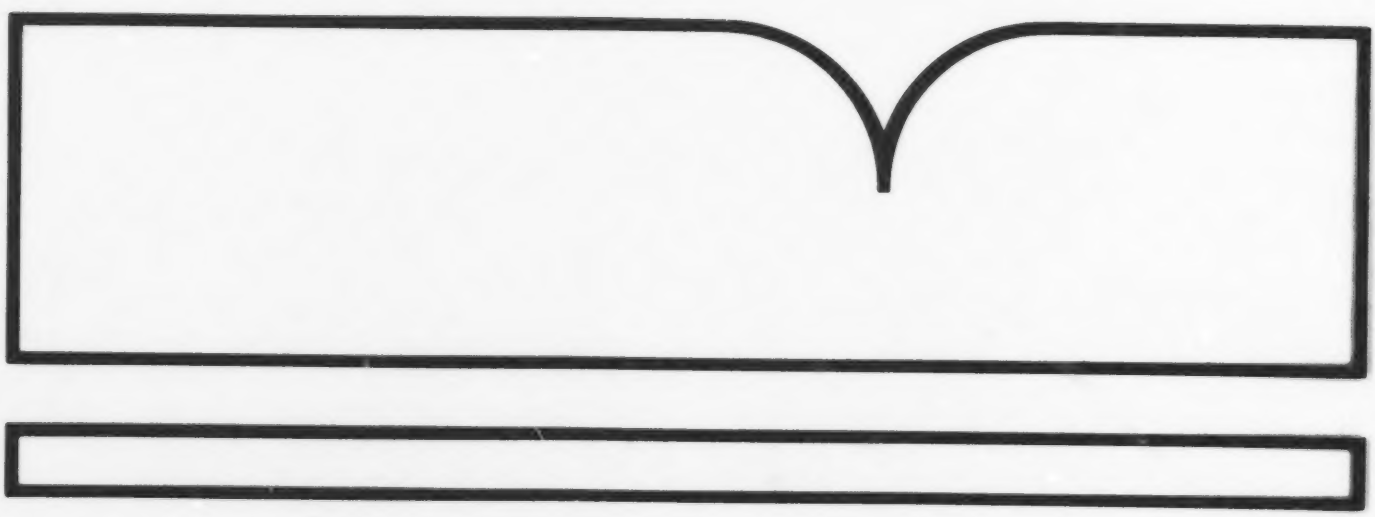
Evaluation of Environmental Stress Imposed by a Coal Ash Effluent Wisconsin Power Plant Impact Study

Wisconsin Univ.-Madison

Prepared for

Environmental Research Lab.-Duluth, MN

Jun 85



U.S. Department of Commerce
National Technical Information Service
NTIS

PB85-213429

EPA/600/3-85/045
June 1985

AN EVALUATION OF ENVIRONMENTAL STRESS IMPOSED BY A COAL ASH EFFLUENT

Wisconsin Power Plant Impact Study

by

Katherine E. Webster
Anne M. Forbes
John J. Magnuson
Department of Limnology
University of Wisconsin-Madison

Grant No. R803971

Project Officer

Gary E. Glass
Environmental Research Laboratory-Duluth
Duluth, Minnesota

This study was conducted in cooperation with
Wisconsin Power and Light Company,
Madison Gas and Electric Company,
Wisconsin Public Service Corporation,
Water Resources Center
and Wisconsin Department of Natural Resources

ENVIRONMENTAL RESEARCH LABORATORY-DULUTH
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
DULUTH, MINNESOTA 55804

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/3-85/045		PB85 213429/AS

4. TITLE AND SUBTITLE	5. REPORT DATE
An Evaluation of Environmental Stress Imposed by a Coal Ash Effluent: Wisconsin Power Plant Impact Study	June 1985
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
K. E. Webster, A. M. Forbes, and J. J. Magnuson	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Center for Limnology University of Wisconsin-Madison Madison, Wisconsin 53706	11. CONTRACT/GRANT NO. 803971
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Environmental Research Laboratory U.S. Environmental Protection Agency Office of Research and Development Duluth, Minnesota 55804	14. SPONSORING AGENCY CODE EPA-600/03

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Effluent discharged from the coal ash settling basin of the Columbia Generating Station (Wisconsin) modified water chemistry (increased trace metal concentrations, suspended solids and dissolved materials) and substrate quality (precipitation of chemical floc) in the receiving stream, the ash pit drain. To test the hypothesis that habitat avoidance could account for declines in macroinvertebrate density observed after discharge began, drift rates of two species were measured in laboratory streams containing combinations of reference and coal ash modified substrate and water. Contrary to the hypothesis, drift was uniformly lower in laboratory streams containing modified substrate and/or water compared to the reference condition for Gammarus pseudolimnaeus and Asellus racovitzai. No preference for the modified condition was shown in a separate substrate-choice experiment.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to public	Unclassified	66
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

DISCLAIMER

This report has been reviewed by the Environmental Research Laboratory-Duluth, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency (EPA) was designed to coordinate our country's efforts toward protecting and improving the environment. This extremely complex task requires continuous research in a multitude of scientific and technical areas. Such research is necessary to monitor changes in the environment, to discover relationships within that environment, to determine health standards, and to eliminate potentially hazardous effects.

One project, which the EPA is supporting through its Environmental Research Laboratory in Duluth, Minnesota, is the study "The Impacts of Coal-Fired Power Plants on the Environment." This interdisciplinary study, centered mainly around the Columbia Generating Station near Portage, Wis., involves investigators and experiments from many academic departments at the University of Wisconsin and is being carried out by the Environmental Monitoring and Data Acquisition Group of the Institute for Environmental Studies at the University of Wisconsin-Madison. Several utilities and State agencies are cooperating in the study: Wisconsin Power and Light Company, Madison Gas and Electric Company, Wisconsin Public Service Corporation, and Wisconsin Department of Natural Resources.

The research presented in this report examined the hypothesis that habitat avoidance could account for declines in macroinvertebrate density observed after effluent began being discharged from the Columbia Generating Station. Drift rates of two species were measured in laboratory streams containing combinations of reference and coal ash modified substrate and water.

Norbert A. Jaworski
Director
Environmental Research Laboratory

ABSTRACT

Effluent discharged from the coal ash settling basin of the Columbia Electric Generating Station (Wisconsin) modified water chemistry (resulting in increased concentrations of trace metals, suspended solids and dissolved materials) and substrate quality (precipitation of a chemical floc) in the receiving stream, the ash pit drain. To test the hypothesis that habitat avoidance could account for declines in macroinvertebrate density observed after discharge began, drift rates of two species were measured in laboratory streams containing combinations of reference and coal ash modified substrate and water. Contrary to the hypothesis, drift was uniformly lower in laboratory streams containing modified substrate and/or water compared to the reference condition for *Gammarus pseudolimnaeus* and *Asellus racovitzai*. No preference for the modified condition was shown in a separate substrate-choice experiment.

In a partial translation of the laboratory experiment to the field, changes in macroinvertebrate distributions at two ash pit drain sites were measured following resumption of coal ash discharge after a 2-week pause. Findings were contradictory. At one site, densities increased after discharge began, while at the other site farther downstream, densities declined. The upstream site may have provided a refuge for invertebrates dislodged from upper reaches of the ash pit drain.

Data on macroinvertebrate community structure from this and other studies was used to evaluate environmental stress at a site receiving coal ash effluent. The following sequence was documented: (1) decline in total abundance and taxa 4 months after effluent discharge began in 1974; (2) loss of most macroinvertebrates in 1977; (3) recovery of the community by 1980, although a shift in dominance to more tolerant species, lower total abundance and a slight decline in diversity, suggested continued sublethal influence of the coal ash effluent.

The variation in the severity of stress suggested by macroinvertebrate community responses was attributable to a series of generating station activities related to coal treatment, effluent discharge characteristics, and dredging of accumulated floc in the upstream drainage ditch. When macroinvertebrate communities were most severely impacted in 1977, effluent discharge and effluent concentration, indicated by conductivity, were at their maximum. The effluent response threshold (1000 µmhos conductivity) proposed in an earlier study, accurately predicted the recovery of ash pit drain macroinvertebrates when effluent concentrations fell below threshold.

CONTENTS

	Page
Foreword	iii
Abstract	iv
Figures	vi
Tables	vii
Acknowledgments	ix
1. Introduction	1
2. Site Description	3
Columbia Electric Generating Station	3
Alterations of Stream Habitats	5
3. Behavioral Responses of Stream Macroinvertebrates to the Coal Ash Effluent	8
Introduction	8
Methods	9
Results	14
Discussion	17
4. Macroinvertebrate Responses to Intermittent Coal Ash Effluent Discharge	19
Introduction	19
Methods	20
Results	22
Discussion	26
5. Effects of the Coal Ash Effluent on Macroinvertebrate Community Structure	31
Introduction	31
Methods	32
Results	35
Discussion	40
6. Evaluation of a Variable Environmental Stress in the Columbia Coal Ash Drainage System	46
Introduction	46
Influence of Generating Station Activities	46
Chemical and Biological Indicators	49
Discussion and Summary	50
References	51

FIGURES

Number		Page
1	Columbia Electric Generating Station	4
2	Laboratory stream chambers	10
3	Plexiglas chambers used in substrate choice experiment	13
4	Results of laboratory drift study	15
5	Daily coal ash effluent discharge into ash pit drain	21
6	Changes in conductance, total filterable solids, macroinvertebrate density and number of taxa upon resumption of coal ash effluent discharge	25
7	Taxonomic composition of artificial substrate samplers	36
8	Abundance of selected taxa	38
9	Shannon-Weaver diversity, evenness, number of taxa, and number of individuals	39
10	Comparison between conductivity, macroinvertebrate abundance and number of taxa at upstream and downstream sites	41
11	Conductivity, effluent discharge rate and frequency between 1974 and 1980	47

TABLES

Number		Page
1	Typical physical and chemical measurements at site APD-1, downstream of the effluent and at the upstream site, APD-3...	5
2	Concentrations of selected trace elements at the point of effluent discharge at site APD-1 and at site APD-3 compared to toxicity thresholds.....	6
3	Treatment combinations tested in the eight laboratory streams.....	11
4	Significant main effects and interactions influencing drift of *Asellus racovitzai*, *Gammarus pseudolimnaeus* and Corixidae in laboratory streams.....	16
5	Median of a series of physical and chemical parameters measured at sites APD-1, APD-2, and RRC before and after effluent discharge began.....	23
6	Correlation between daily effluent discharge rate and a series of chemical and physical parameters measured at sites APD-1 and APD-2.....	24
7	Taxonomic composition of ponar samples collected at the two experimental sites and at the reference site.....	27
8	Comparison of two models describing macroinvertebrate response to resumption of coal ash effluent discharge.....	29
9	Results from multiple comparison test.....	29
10	Dates showing intervals for macroinvertebrate colonization of artificial substrate samplers in the ash pit drain.....	32
11	Comparison of macroinvertebrate taxa colonizing basket and modified Dendy samplers at site APD-1.....	34
12	Summary of experimental studies investigating macroinvertebrate responses to coal ash effluent.....	42

Number		Page
13	Summary of observations on conductivity and extent of floc deposits at site APD-1 and a set of generating station activities potentially influencing ash pit drain habitats....	48
14	Estimates of severity of enviromental stress at APD-1 based on chemical and biological indicators.....	49

ACKNOWLEDGMENTS

Jim Koenig, Paula Kuzmarski, Walter Gauthier, and Jean Brussock helped in the field and laboratory. Walter Gauthier built the laboratory stream chambers with the help from Glen Lee, who also assisted with the construction of many laboratory apparati. Stephen Lozano, Dennis Rondorf, and Bill Horns assisted in experimental design and statistical analysis. William Hilsenhoff, Cynthia Duszkowski, William Tonn, Thomas Frost, and Joseph Eilers provided advice and new insights into the data set. Cheryle Hughes drafted many of the figures.

Financial assistance was provided by the U.S. Environmental Protection Agency (Grant No. R803971) with additional funds from the University of Wisconsin-Madison, Madison Gas and Electric Company, the Wisconsin Public Service Corporation and the Wisconsin Public Service Commission. This assistance, as well as that provided by the Water Resources Center, University of Wisconsin, is gratefully acknowledged.

SECTION 1

INTRODUCTION

Discharge of coal ash supernatants from wet storage ponds at coal-fired power plants can have a significant impact on aquatic ecosystems (Cherry et al. 1979, Coutant et al. 1978, Crossman et al. 1974). Acute and sublethal impacts on aquatic organisms can occur in response to one or more of the stresses typically associated with coal ash effluent discharge: (1) the addition of elements to the ecosystem, including some potentially toxic heavy metals, (2) increases in suspended solids, (3) changes in pH and chemical balance, (4) sedimentation of chemical solids, and (5) absorption of P by fly ash interfering with nutrient cycling (Guthrie et al. 1982, Roy et al. 1981).

The Columbia Electric Generating Station near Portage, Wisconsin, consists of two coal-fired operating units, each capable of producing 527 MW/day. Fly ash from Unit I and bottom ash from both units are slurried into a series of settling basins. The coal ash effluent is discharged into a stream, the ashpit drain, situated in a floodplain of the Wisconsin River. This discharge severely modified stream habitats through precipitation of a chemical floc and increases in suspended and dissolved materials, including some toxic heavy metals (Magnuson et al. 1980a; Andren et al. 1977).

Habitats believed to receive severe impacts included a 5 km stretch of the ash pit drain (Forbes et al. 1981). The structure of the ash pit drain's macroinvertebrate community, first monitored prior to generating station operation, showed dramatic declines in density and species richness in response to these environmental stresses (Magnuson et al. 1980a). Hypotheses proposed to explain these responses were tested in a series of laboratory and field manipulations (Forbes et al. 1981; Forbes and Magnuson 1980; Magnuson et al. 1980 a,b). Direct toxicity and sublethal responses associated with the uptake and accumulation of toxic metals, reductions in food quality, and declines in metabolism, were observed.

None of the mechanisms explored in the previously described studies fully explained the declines in field distributions. One of the purposes of the research reported here was to investigate a third hypothesis based on a behavioral response of habitat avoidance. In one study, the drift responses of stream invertebrates to coal ash chemicals were measured in laboratory streams (Section 3) (Webster et al. 1981). A second study (Section 4) attempted to verify the laboratory drift results in the field by observing

changes in macroinvertebrate distributions following resumption of coal ash discharge after a 15-day pause in effluent discharge.

The final two sections evaluate the severity of environmental stress at one ash pit drain site. Section 5 extends the study conducted by Magnuson et al. (1980a), by comparing their 1974, 1975 and 1977 macroinvertebrate distributions with the recovery observed in 1980. Community and species responses are examined and compared with examples from other pollutional stresses. Throughout the 7-yr study period (1974-80), observations on macroinvertebrate distributions and chemical measures of habitat modification, indicated a variable intensity of environmental stress. At the same time studies were being conducted, effluent discharge characteristics, methods of coal and effluent treatment, and other generating station activities were changing. The impact of these activities on the severity of environmental stress observed in the coal ash drainage system is discussed in Section 6.

Much attention has been focused on other serious environmental problems associated with the operation of coal-fired power plants, including emissions of sulfur oxides that contribute to acidic deposition, release of thermal discharges, entrainment, and chlorine toxicity. Environmentally sound disposal of two of the major byproducts of coal consumption -- power plant aggregate (bottom ash and slag) and fly ash -- is likely to become an equally pressing concern as the volume of waste being generated increases. Although the Clean Water Act of 1977 prevents newly constructed coal-fired power plants from using wet storage of ash residues, this method of disposal was prevalent prior to passage of the act. The results of this research support the need for stricter control on the amount of effluent discharged into lotic environments by these older power plants.

SECTION 2

SITE DESCRIPTION

COLUMBIA ELECTRIC GENERATING STATION

The Columbia Electric Generating Sttion was constructed in 1972 on 1100 ha of Wisconsin River floodplain near Portage, Wisconsin (Figure 1). Two operating units each produce 527 MW of electricity, burning 5,000 to 10,000 tons of low S western coal per day. Units I and II began operation in April 1975 and March 1978, respectively.

The low S pulverized coal typically contains 7 to 8% ash. Approximately 98% of the fly ash residue is collected by high energy electrostatic precipitators located in the stacks. Fly ash from Unit I is deposited as a slurry into Sector I of a 30-ha settling basin north of the generating station. Fly ash from Unit II is disposed of dry. Water from Sector I drains directly through the dike walls into the final settling pond (Sector III). Water from Sector II, which receives bottom ash slurried from the boilers of both units, is circulated back into the plant and pumped into Sector III when water levels are excessively high, usually only in winter. Prior to the summer of 1977, the settling basin was divided into a primary settling pond, which received fly ash and bottom ash, and a secondary settling pond.

High concentrations of reactive metal oxides raise the pH of water in the final settling basin to 10 or 11 (Andren et al. 1977). To meet Wisconsin stream water quality standards the effluent is acidified upon discharge into a shallow ditch that flows along the eastern boundary of the cooling lake (Figure 1). About 2 km downstream, the effluent ditch joins the ash pit drain, a creek draining a wetland and mint farm east of the generating station site. The ash pit drain flows through an artifically ditched channel along the east and south borders of the cooling lake. In contrast to ash pit drain reaches upstream from the effluent which are characterized by unconsolidated organic substrates, substrates in the ditched area are predominantly sandy with small patches of water grasses and sedges. Depth is relatively constant across the width of the stream (approximately 5 m) due to the ditched stream bed. Riffles are rare, stream banks are grassed with a few small shrubs. Approximately 5 km from the point of discharge, the effluent enters a wetland and floodplain forest where it joins Rocky Run Creek (RRC), a tributary to the Wisconsin River. This creek originates in a marsh lake and flows through 20 km of agricultural land before reaching the generating station site (Magnuson et al. 1980a).

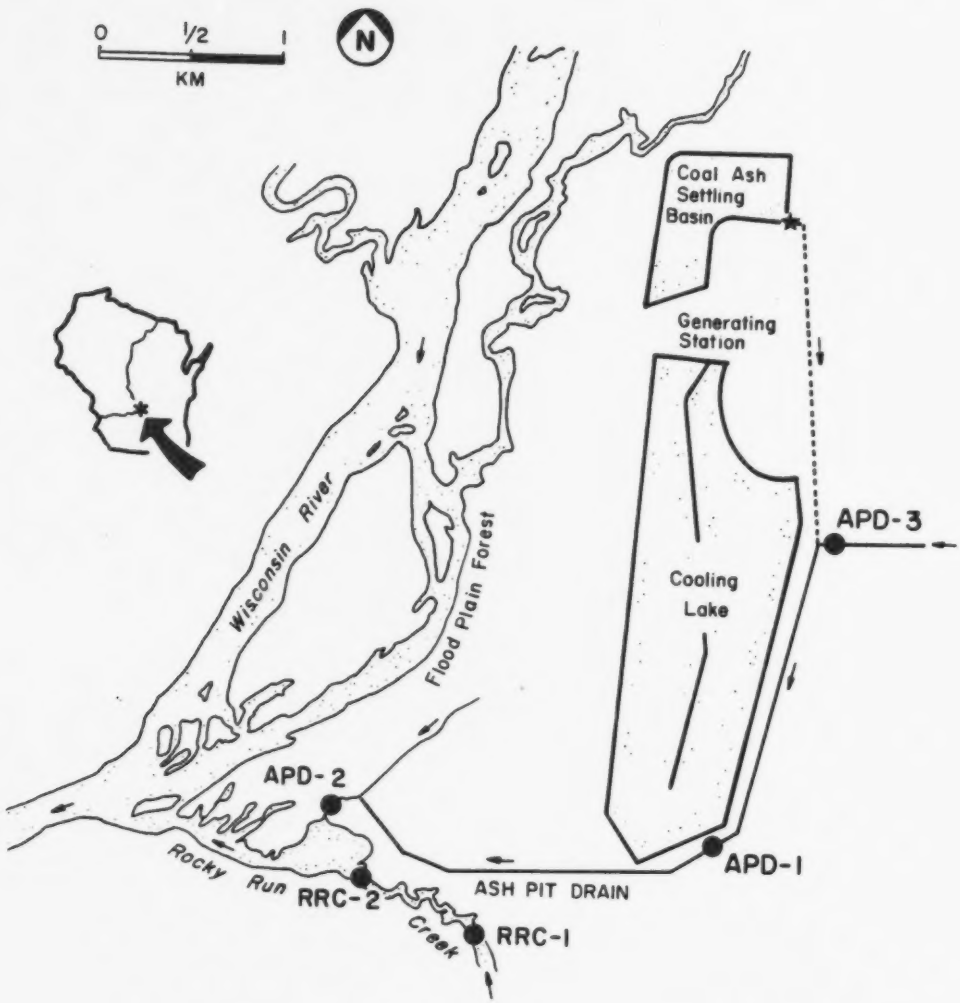


Figure 1. Columbia Electric Generating Station study site. Sampling locations marked with closed circles. Arrows denote direction of flow. The star marks the point of coal ash effluent discharge from the settling basin into the effluent ditch (dashed line) which joins with the ash pit drain (solid line).

ALTERATIONS OF STREAM HABITATS

Water Quality

Magnuson et al. (1980a) observed alteration of several water quality parameters due to coal ash chemicals. Their 1977 results are summarized in Table 1. In 1977 the downstream site (APD-1) had higher conductivity and turbidity but lower alkalinity than the upstream site (APD-3). Temperature and pH increased slightly at APD-1. Concentrations of the trace elements Cr, Ba, Al, Cd, and Cu in dissolved form and Cr, Al and Ba in samples of suspended particulates were higher at downstream sites compared to upstream sites in 1977 (Table 2) (Andren et al. 1977, Helmke et al. 1976a,b). Concentrations of Cd, Cr, and Cu approached water quality criteria for aquatic life suggested by the U.S. Environmental Protection Agency (1976, 1980).

TABLE 1. TYPICAL PHYSICAL AND CHEMICAL MEASUREMENTS AT SITE APD-1, DOWNSTREAM OF THE EFFLUENT AND AT THE UPSTREAM SITE, APD-3. DATA BASED ON TWO SAMPLES COLLECTED IN SEPTEMBER AND OCTOBER 1977 (MODIFIED FROM MAGNUSON ET AL. (1980a)

Parameter (Units)	Downstream Site APD-1	Upstream Site APD-3
Temperature (C)	21.1	18.0
Current speed (cm/sec)	21.4	8.0[a]
Dissolved oxygen (ppm)	8.6	7.6
Conductivity (μmhos 25C)	2515.0	454.0
Alkalinity (ppm)	93.8	250.2
Hardness (ppm)	130.0	244.4
pH	7.35	7.45
Turbidity	27.0	3.8

[a]Typical value at site APD-3 on other dates.

Conductivity provided an easily monitored measure of gradients of effluent strength (Forbes et al. 1981). A major source of this conductivity in the coal-ash effluent was the addition of $NaCO_3$ to pulverized coal to increase efficiency of fly ash collection in the electrostatic

TABLE 2. CONCENTRATIONS OF SELECTED TRACE ELEMENTS (PPM) AT THE POINT OF EFFLUENT DISCHARGE, AT SITE APD-1, AND AT SITE APD-3 COMPARED TO TOXICITY THRESHOLDS MODIFIED FROM MAGNUSON ET AL. (1980a)

Element	Water Quality Criteria	Ashpit Discharge	APD-1	APD-3
Dissolved[a]				
Al	--	0.100-11.4	0.045-0.476	0.003-0.165
Ba	50.0[b]	0.730	--	--
Cd	0.012[c]	0.0021-0.0031	0.0001-0.0012	0.0001-0.0002
Cr	0.100[c]	0.014-0.077	0.006-0.028	0.001
Cu	0.022[d]	0.004-0.045	0.002-0.024	<0.0003-0.002
Suspended particulates[e]				
Ba	--	17,240	1.294	107
Cr	--	134	1.225	--

[a]Ba concentrations from Helmke et al. (1976b); other dissolved elements from November 1976 to April 1977 observations in Andren et al. (1977).
[b]Suggested as a toxicity level, but not proposed as water quality criteria by U.S. Environmental Protection Agency (1976).
[c]U.S. Environmental Protection Agency (1976).
[d]U.S. Environmental Protection Agency (1980).
[e]Helmke et al. (1976a) fall 1975 data; Al was an important constituent of suspended particulates, but could not be measured by neutron activation analysis.

precipitators. The extreme conductivities measured where the effluent joined the ash pit drain (e.g., 3000 µmhos in 1977) progressively declined as the effluent was diluted by water leaking from the cooling lake (Andrews and Anderson 1976) and mixed with waters of the ash pit drain, sedge meadow and Rocky Run Creek. The conductivity of Wisconsin River water was not affected below the entry of Rocky Run Creek (Magnuson et al. 1980a).

Substrate Quality

Substrates in the ash pit drain prior to plant operation were silty with high organic content (Magnuson et al. 1980a). After generating station operation began, substrates in the artificially ditched reaches of the ash pit drain became more sandy as silt was washed away (Magnuson et al. 1980a). Acidification of the effluent caused precipitation of oxides of elements such as Al, Ba and Cr into a flocculent material (Andren et al. 1977). This floc coated stream substrates at the downstream sites in 1977 and 1978 and was carried by the current into Rocky Run Creek and the Wisconsin River (Forbes et al. 1981, Magnuson et al. 1980a). Extensive areas of the ash pit drain and the slough near Rocky Run Creek were covered by thick deposits of floc during low flow conditions in the falls of 1977 and 1978. Spring flooding removed much of the accumulated layer (Forbes et al. 1981). Floc deposits were not nearly as extensive in the fall of 1979 having disappeared from much of the ash pit drain. Deposits were only observed in backwater pools among patches of grases and sedge growing on the otherwise open sandy substrates in the main channel.

SECTION 3

BEHAVIORAL RESPONSES OF STREAM MACROINVERTEBRATES TO THE COAL ASH EFFLUENT

INTRODUCTION

Examination of effects of pollution on stream macroinvertebrates has generally focused on acute toxicity. Considerably less attention has been directed toward investigating behavioral responses to sublethal habitat modifications by pollutants. While catastrophic downstream movement or drift accompanied by depletion of standing crop can result from toxic pollutant stress (Coutant 1964; Waters 1972), behavioral drift has been recognized as an important mechanism by which macroinvertebrates can avoid unfavorable environments (Corkum et al. 1977). In the field, increased drift of stream macroinvertebrates has been induced by stream acidification (Hall et al. 1980) and sediment addition (Rosenberg and Wiens 1978). In laboratory streams, unfavorable substrate type, current velocity, and lack of food supply have increased the drift response (Otto 1976; Corkum et al. 1977; Walton 1978).

Previous studies documented changes in macroinvertebrate distributions in stream habitats modified by a coal ash effluent from an electric generating station in Columbia Co., Wisconsin (Forbes et al. 1981; Magnuson et al. 1980a). After generating station operation began in April 1975 the abundance of most taxa inhabiting the ash pit drain declined. In 1977 few individuals and taxa colonized artificial substrate samplers, indicating an even more impoverished community. In Rocky Run Creek, downstream of the junction with the ash pit drain, colonization of artificial substrates was reduced only when coal ash effluent concentrations, indicated by conductivity, were high (Forbes et al. 1981). Since declines in abundance and species diversity could not be adequately explained by direct toxicity, field distributions might be explained by habitat avoidance through increased drift response. Macroinvertebrate drift responses to a coal ash modified habitat simulated in laboratory streams were used to test this hypothesis. The results of this study have previously been published (Webster et al. 1981).

Water quality degradation has generally been the focus of studies of the impacts of pollutant discharges into lotic environments. However, the effluent altered both water and substrate quality in the coal ash drainage system. Substrate characteristics generally determine macroinvertebrate habitat preferences, while physical and chemical factors determine habitat tolerance (Cummins 1966, Cummins and Lauff 1969). Decreases in

macroinvertebrate diversity attributed to declines in water quality have been more closely correlated with substrate parameters (Ruggiero and Merchant 1979). The experimental design used was developed to allow evaluation of the relative importance of substrate, water, and food quantity changes on the macroinvertebrate drift response.

METHODS

Drift Experiment

Macroinvertebrate drift was measured in laboratory streams containing combinations of substrate and water collected from two sites, one contaminated by coal ash effluent (APD-1) and the other an unaffected reference site in Rocky Run Creek (RRC-1) (Figure 1). A third treatment of food addition was included to investigate possible food limitation in the coal ash effluent-modified substrates.

Laboratory Streams--

The design of the plexiglas laboratory streams (Figure 2) was modified from Gee and Bartnik (1969). A current generated by airstones circulated water within each laboratory stream over a channel 11 x 52 cm. Nets of fiberglass screen collected organisms that drifted to the end of each channel. Two replicate experiments were run in a controlled environment room. Temperature (5.0 C) and photoperiod (12L:12D) approximated the field conditions at the time of the study in March 1979. Laboratory streams were illuminated by 15-W fluorescent lamps controlled by a timer set to the ambient photoperiod.

Macroinvertebrates--

Macroinvertebrates were collected from the reference site RRC-1 in Rocky Run Creek, upstream of its junction with the ash pit drain, 2 weeks before each experiment, and kept static in aerated buckets at the experimental temperature and photoperiod. Representatives from five taxa were selected: Isopoda (*Asellus racovitzai*), Amphipoda (*Gammarus pseudolimnaeus*), and aquatic insects from the orders Hemiptera (*Hesperocorixa* sp. and *Sigara* sp.), Ephemeroptera (*Leptophlebia* sp. and *Callibaetis* sp.) and Trichoptera (*Pycnopsyche* sp.).

Substrate, Water and Food Addition--

Macroinvertebrate drift was measured in response to two levels of each of three treatments -- substrate, water, and food addition (Table 3). Substrates were collected from the reference site and from the modified habitat 2 weeks before the experiments and were frozen to eliminate macroinvertebrates. Water was collected from the same two sites on the day before the experiments. The presence or absence of shredded sugar maple

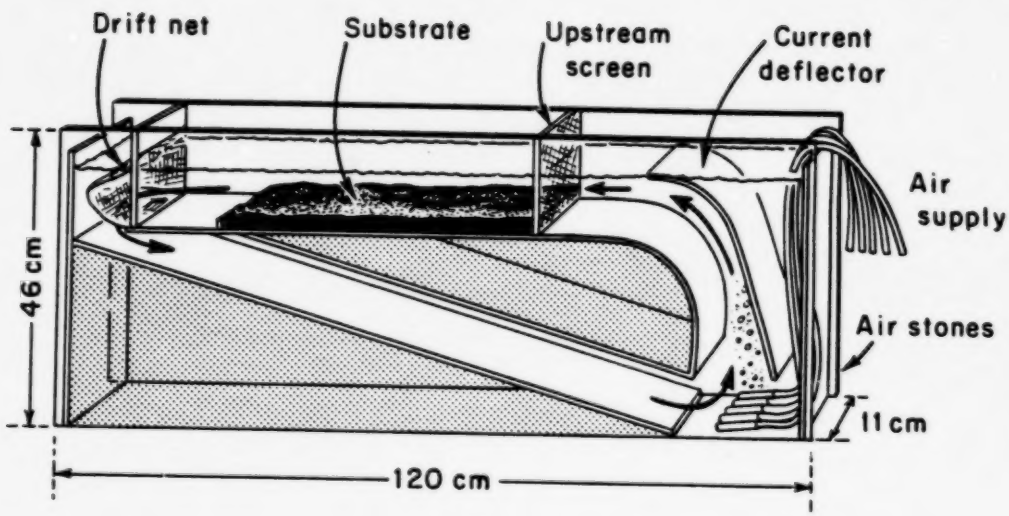


Figure 2. Laboratory stream chamber. Arrows denote the direction of flow along the 52-cm stream channel located between the upstream screen and drift net. Shaded areas do not contain water. This design was modified from that of Gee and Bartnik (1969).

Acer saccharum leaves, incubated in mesh bags in Rocky Run Creek for 4 months, represented the food addition treatment.

TABLE 3. TREATMENT COMBINATIONS TESTED IN THE EIGHT LABORATORY STREAMS[a]

Stream Chamber	Substrate	Water	Food
1	M	M	+
2	R	M	+
3	M	R	+
4	R	R	+
5	M	M	0
6	R	M	0
7	M	R	0
8	R	R	0

[a]For the factors substrate and water, M is coal ash modified site and R is reference site; for food addition + is food added and 0 is no food added.

Experimental Procedure--

Treatment combinations were randomly assigned to laboratory streams. Thawed substrates were added to the stream channels to a depth of 2 cm. After circulating distilled water continuously within the streams for 24 h to remove easily suspended materials from the substrates, the streams were drained and filled with the appropriate treatment waters to a depth of 9 cm. Shredded leaf material was partially buried at the surface of the substrates in those streams that received the food treatment. A total of 37 individuals (10 *Asellus racovitzai* , 10 *Gammarus pseudolimnaeus* , 10 Corixidae, 5 Ephemeroptera, and 2 Trichoptera) were placed in the upstream third of each stream channel and allowed to acclimate to experimental conditions for 2 h without current. After starting water circulation, the drift nets at the end of each channel were emptied and drifting organisms counted after 1 h and every 3 h thereafter for 48 h. At the conclusion of each trial, nondrifting invertebrates were recovered from the sediments. Missing individuals were counted as mortalities.

Water Analysis--

Temperature and current speed were monitored throughout the experiment using a mercury thermometer and a 4-cm drogue, respectively. Dissolved oxygen levels were measured by the Winkler Method (American Public Health Association 1976). At the end of 48 h water samples from each laboratory stream and from unused water from the reference and modified sites were analyzed for methyl orange alkalinity (American Public Health Association 1976), total dissolved residue (American Public Health Association 1976), conductivity (YSI Model 33 Conductivity Meter) and pH (Orion Model 339A pH meter).

Data Analysis--

The effects of the three treatments (substrate, water and food) at two levels each on macroinvertebrate drift was measured using a 2^3 factorial design (Box et al. 1978). All treatment combinations (Table 3) were tested simultaneously in the eight laboratory streams; the entire run was replicated. Such a design allows pairwise comparison of means within each treatment or main effect (sample size of eight for each treatment level) as well as evaluation of interactions between treatments (sample size of four for each of four possible combinations).

Data for *Asellus racovitzai*, *Gammarus pseudolimnaeus* and corixids were analyzed separately using a three-way analysis of variance (RUMMAGE VER 3, Madison Academic Computing Center), with the number drifting as the dependent variable. Since nearly all Ephemeroptera, Trichoptera, and corixids had drifted by 48 h in all treatments, the data from these taxa did not meet the assumptions for ANOVA and were not analyzed.

Substrate Choice Experiment

In August 1979 the substrate preferences of *Gammarus pseudolimnaeus* offered a choice between sediments from the ash effluent modified site and from the reference site were investigated. Plexiglas chambers (30 x 16 x 11 cm) contained substrates on either side of a 2.0-cm high longitudinal divider (Figure 3). Twenty chambers were randomly placed in respect to a light source (15-W incandescent lamps) in a constant temperature water bath. Ten of the chambers received only reference substrates (pretreated by freezing as previously described) and served as controls. The other 10 chambers contained two substrates randomly assigned to the right or left side. On one side, 2.0 cm of reference substrate was added; on the other, ash effluent modified substrates were layered over reference substrates. All chambers contained fresh reference site water and were aerated. Experimental conditions of temperature (22C) and photoperiod (14L:10D) approximated ambient field conditions.

Ten *Gammarus pseudolimnaeus* were introduced into each chamber, five per side. At the end of 48 h the chamber halves were separated by a plexiglas divider and the *Gammarus* settling on each side were recovered. Data were

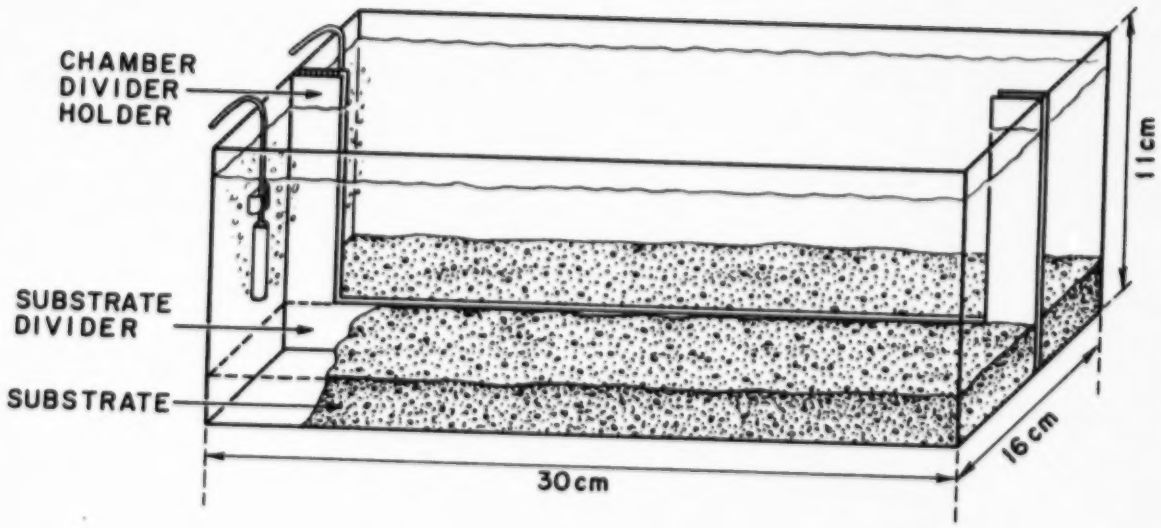


Figure 3. Plexiglas chamber used in substrate choice experiment. Different substrates were placed on either side of a divider. The chamber could be divided in half by a plexiglas sheet placed inside the chamber divider holder.

pooled separately for treatment and for control chambers and analyzed using the chi-square method.

RESULTS

Drift Experiment

Factors Influencing Drift after 48 h--

The hypothesis that aquatic macroinvertebrates would drift at higher rates in laboratory streams with modified conditions was not supported by the patterns of drift observed for *Gammarus* and *Asellus*. The highest drift occurred in stream chambers containing substrate and water from the reference site (Figure 4).

Asellus racovitzai drifted more in response to food addition compared to no food addition and in reference substrates compared to modified substrates. The significant response to substrate should be considered as part of the substrate-water interaction. Drift was significantly higher in streams where substrate and water were from the reference site compared to all other stream chambers, while drift in streams with modified substrate and reference water was significantly lower.

Except for a non-significant effect of food addition, *Gammarus pseudolimnaeus* exhibited similar responses. Drift increased in the reference substrate and the substrate-water interaction was significant. Again, the highest drift occurred in laboratory streams containing substrate and water from the reference site.

Drift rates during the first hour were low for *Asellus racovitzai* (4%) and *Gammarus pseudolimnaeus* (10%). Drift activity of the remaining *Asellus racovitzai* occurred predominantly during the night hours (38%) compared to the day (5%). In contrast, the Gammarids were collected in roughly equivalent numbers during light (15%) and dark (13%) periods. In general, drifting invertebrates in streams exhibit a diel periodicity, with higher rates during the night (Waters 1972). This pattern was not exhibited by *Gammarus pseudolimnaeus* in the laboratory streams.

Changes in Significant Factors Influencing Drift over Time--

To determine whether the factors influencing drift changed over time, similar analyses of drift were made at 12 and 24 h (Table 4). For *Asellus*, no main effects or interactions were significant at 12 h; by 24 h, drift was significantly higher in chambers with food added. The influence of substrate did not become important until 48 h. For *Gammarus*, no factors were significant at 12 h; by 24 h the substrate-water and substrate-food interactions were significant.

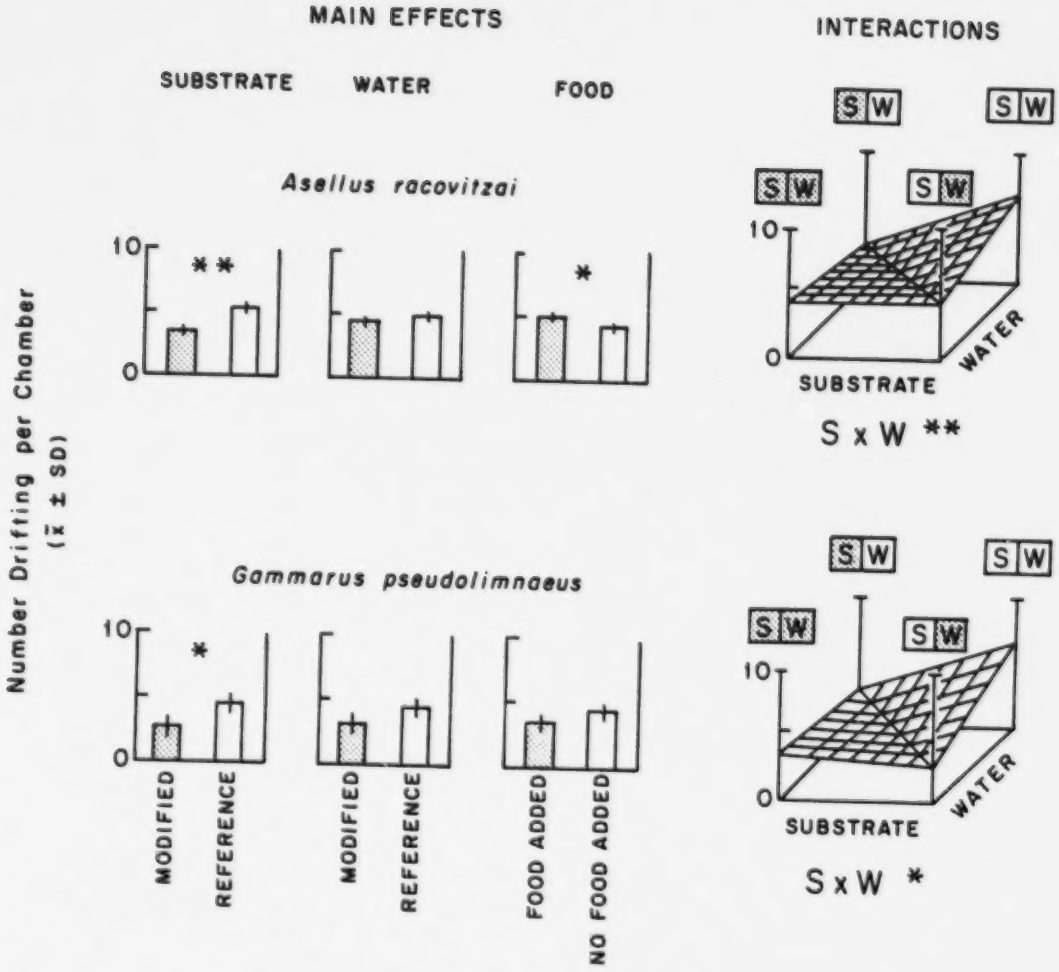


Figure 4. Results of laboratory drift study. Number of individuals drifting per stream chamber in response to each of the main effects considered separately (mean ± S.D.) on the left and the significant substrate-water interactions on the right. In the latter plots, each y-axis shows average drift at the levels of substrate (S) and water (W) denoted by the boxes above each axis. Significant levels are denoted by * (0.05) and ** (0.001).

TABLE 4. SIGNIFICANT MAIN EFFECTS AND INTERACTIONS INFLUENCING DRIFT OF *ASELLUS RACOVITZAI*, *GAMMARUS PSEUDOLIMNAEUS*, AND CORIXIDAE IN LABORATORY STREAMS AFTER 12, 24 AND 48 h. SUB|X|WATER AND SUB|X|FOOD DENOTE THE SUBSTRATE-WATER AND SUBSTRATE-FOOD INTERACTIONS, RESPECTIVELY

Macroinvertebrate Taxon	12 h	24 h	48 h
Asellus racovitzai	None	Food*	Substrate* Food* Sub|x|Water*
Gammarus pseudolimnaeus	None	Sub|x|Water* Sub|x|Food*	Substrate* Sub|x|Water*
Corixidae	Water** Food*	Food*	([a])

*$p < 0.05$.
**$p < 0.001$.
[a]Data are non-normal.

Results of the analysis of the corixid drift response at 12 and 24 h suggested that initially (12 h) the main effects of water and food were important; only the effect of food was significant at 24 h. Drift in those cases was higher in reference site water and with food addition. By 48 h nearly all Corixidae had drifted in all stream chambers.

Analysis of Mortalities--

There was no evidence for differential mortality between stream chambers or treatments. Analyses of variance using the numbers of *Asellus* and *Gammarus* missing or found dead in each stream chamber after 48 h revealed only one significant effect (the substrate by food interaction for *Gammarus* at $p < 0.05$). Mortality was highest in chambers with modified substrate and food addition but was low in all other chambers.

Water Quality--

Water quality measurements corresponded to typical field measurements from earlier studies (Magnuson et al. 1980a) with the exception of ash pit drain conductivity. As discussed previously, conductivity was lower in the ash pit drain after January 1979. For laboratory streams containing water from reference and modified sites, respectively, average alkalinities were 200 and 100 mg/liter $CaCO_3$, conductivities were 430 and 530 µmhos/cm and pHs were 8.3 and 8.0. Those values were comparable to concentrations measured

in unused water from each site. Dissolved oxygen values were near saturation in all stream chambers. Total dissolved residue values were erratic, possibly due to inadvertent siphoning of substrate material into the sample containers. Temperatures ranged from 4.4 to 5.1 C and current speeds from 5.2 to 5.8 cm/sec.

Substrate Choice Experiment

The hypothesis tested was that *Gammarus pseudolimnaeus* would display no preference for modified substrates. Chi-square analysis of data from the control chambers showed that amphipods did not discriminate between chamber sides (right vs. left or position in respect to light source) after 48 h. Likewise, no differences were observed between modified and reference substrates (χ^2 = 0.40 for pooled data from 10 chambers).

DISCUSSION

Drift of the benthic invertebrates *Gammarus pseudolimnaeus* and *Asellus racovitzai* in laboratory streams was influenced by substrate and water quality. Food addition in the form of detritus played a secondary role. In contrast, the Corixidae, which usually inhabit the weedy margins of streams, drifted in high numbers under all conditions at the end of 48 h; the habitat provided was not their natural one. Water and food were significant influences on early drift rates.

The results do not support the hypothesis that macroinvertebrates avoid habitats modified by the coal ash effluent through increased drift. To the contrary, the drift of *Gammarus pseudolimnaeus* and *Asellus racovitzai* was uniformly lower in laboratory streams where substrate, water, or both were from the modified site. This result suggests an effect due to chemical constituents of the coal ash effluent present in the sediments and water.

The reduced drift response observed could result from a preference for the modified over the reference conditions or from a reduction in activity in modified habitats. Preference for the modified habitat seems unlikely. When presented a choice *Gammarus pseudolimnaeus* did not distinguish between modified and reference substrates.

Although no evidence was found for behavioral avoidance of coal ash-modified habitats in the 1979 laboratory drift study, this cannot be totally discounted as a partial explanation for the lack of organisms present in 1977. Habitat modifications were less severe in 1979 and a fall survey demonstrated that a community dominated by *Asellus racovitzai* and *Hyallela azteca* had recolonized the ash pit drain (Section 4). The coal ash-modified habitat simulated in the laboratory streams may not have represented the severity of environmental stress that occurred in 1977 or accurately reproduced the field condition.

Sublethal effects on arthropod physiology following exposure to the same coal ash effluent have been documented. Crayfish metabolism, as

measured by oxygen consumption, was significantly lower after 10 weeks of exposure to ash effluent-modified habitats as compared to controls (Magnuson et al. 1980a).

Changes in invertebrate behavior have been observed following exposure to sublethal concentrations of other pollutants. Maciorowski et al. (1980) observed a decline in locomotor activity levels of the crayfish (*Cambarus acuminatus*) when exposd to sublethal Cd concentrations. They suggest that disruption of crayfish chemoreceptive sensitivity may have caused the altered behavioral patterns. Similarly, the coal ash effluent which contains sublethal concentrations of several heavy metals (Table 2) may have depressed the physiological activity of the stream invertebrate studies.

If behavior can be interpreted as a manifestation of underlying biochemical and physiological responses to environmental contaminants (Sherer 1976), the results of this study provide further evidence of sublethal stress imposed by the coal ash effluent. Sublethal concentrations of toxic materials may have a more devastating impact on benthic communities than acute pollutants, affecting not only behavior, but also fecundity, longevity and reproduction (Lehmkuhl 1979).

SECTION 4

MACROINVERTEBRATE RESPONSES TO INTERMITTENT COAL ASH EFFLUENT DISCHARGE

INTRODUCTION

The laboratory drift study (Section 3) demonstrated a reduction in drift activity of macroinvertebrates exposed to coal ash chemicals. This result did not support the hypothesis of habitat avoidance proposed to explain the lack of macroinvertebrates at severely stressed sites in 1977. In 1979 when the laboratory drift study was performed, effluent concentrations were below the 1000 μmhos conductivity threshold observed for a series of acute and sublethal responses measured in 1977 (Forbes et al. 1981). Thus, while the drift study may not have been a true test of a mechanism operating earlier, it did provide evidence for sublethal impacts on activity at concentrations below the effluent response threshold. Later observations of macroinvertebrate community structure support this contention: although populations recovered when effluent concentrations declined, the structure was characteristic of a disturbed community (Section 5).

In October 1979, an attempt was made to further quantify the influence of sub-threshold coal ash effluent concentrations on macroinvertebrate distributions. A plot of daily effluent discharge rates from June-October 1979 (Figure 5) shows that the Columbia Generating Station did not continuously discharge effluent. After varying periods of time stream water quality would revert to background conditions. This intermittent discharge pattern was used to examine the response of the macroinvertebrate community to renewed effluent exposure. These conditions offered a partial translation of the laboratory drift study to a field situation; an important difference was the lack of control over substrate quality in the field.

The objectives of this study were: (1) to document changes in macroinvertebrate abundance and species composition attributable to renewed discharge of the coal ash effluent; (2) to determine if intensity of response varied with effluent concentration; (3) to attempt to verify the results of the laboratory drift study in the field; and (4) to evaluate the sublethal stress on the macroinvertebrate community imposed by the intermittent effluent discharge pattern.

METHODS

Study Design

Benthic macroinvertebrates were sampled on two dates prior to effluent release (October 3 and 4) and on the first, second, fourth and eighth days of discharge (October 5, 6, 8 and 12) (Figure 5). Pumping of the effluent began at 0300 on October 5. The last discharge prior to this date occurred on Septembr 20, 15 days earlier.

Two experimental sites were chosen for study: APD-1 and APD-2, located 1.7 and 3.4 km, respectively, downstream of the junction of the ash pit drain and the effluent ditch (see Figure 1). A reference site (RRC-2) in Rocky Run Creek 0.5 km upstream of its junction with the ash pit drain was also sampled to estimate natural population variability. Differences in stream habitat characteristics preclude use of this site as a strict control for the two experimental sites.

Macroinvertebrate Sampling

Benthic macroinvertebrates were collected with a Wildco Petite ponar (open jaw 15 x 17 cm). Triplicate samples were taken at each site. At sites APD-1 and APD-2, organisms were collected within patches of sedges (*Eleocharis acicularis*; personal communication Judy Capelli, 1980) and grasses rather than from the surrounding predominantly sandy substrates. Substrates at RRC-2 were more homogeneous, consisting mainly of fine silt and detrital material.

Upon collection, the contents of each ponar grab were emptied into a bucket with a fine wire mesh bottom and backwashed with stream water to remove excess silt. The remaining material was stored in double plastic bags and preserved with buffered formalin (5%). In the laboratory, invertebrates collected in each ponar sample were hand sorted and individuals counted. Only *Asellus racovitzai* in APD-1 samples were subsampled. Identification was to genus except for Hirudinea, Tricladida and some aquatic insects which were only identified to family (e.g., Chironomidae).

Chemical and Physical Data

Conductivity (Yellow Springs Instrument Model 33 SCT meter), current speed (Ocean Equipment Model 451), sample depth, and temperature were measured at each site on each date. Grab water samples were analyzed in the labortory for methyl orange alkalinity (American Public Health Association 1976), turbidity (Hach Model 2100A), pH (Orian Model 399A) and total filterable residue (TFR) (American Public Health Association 1976). The top 8 cm of stream sediments were collected near the site of each ponar sample with a 1-m length of 9.5-mm tygon tubing capped with a pipette bulb (Forbes et al. 1981). In the laboratory, 7.5 ml of each sediment sample was thoroughly mixed with an equal volume of distilled water in a graduated

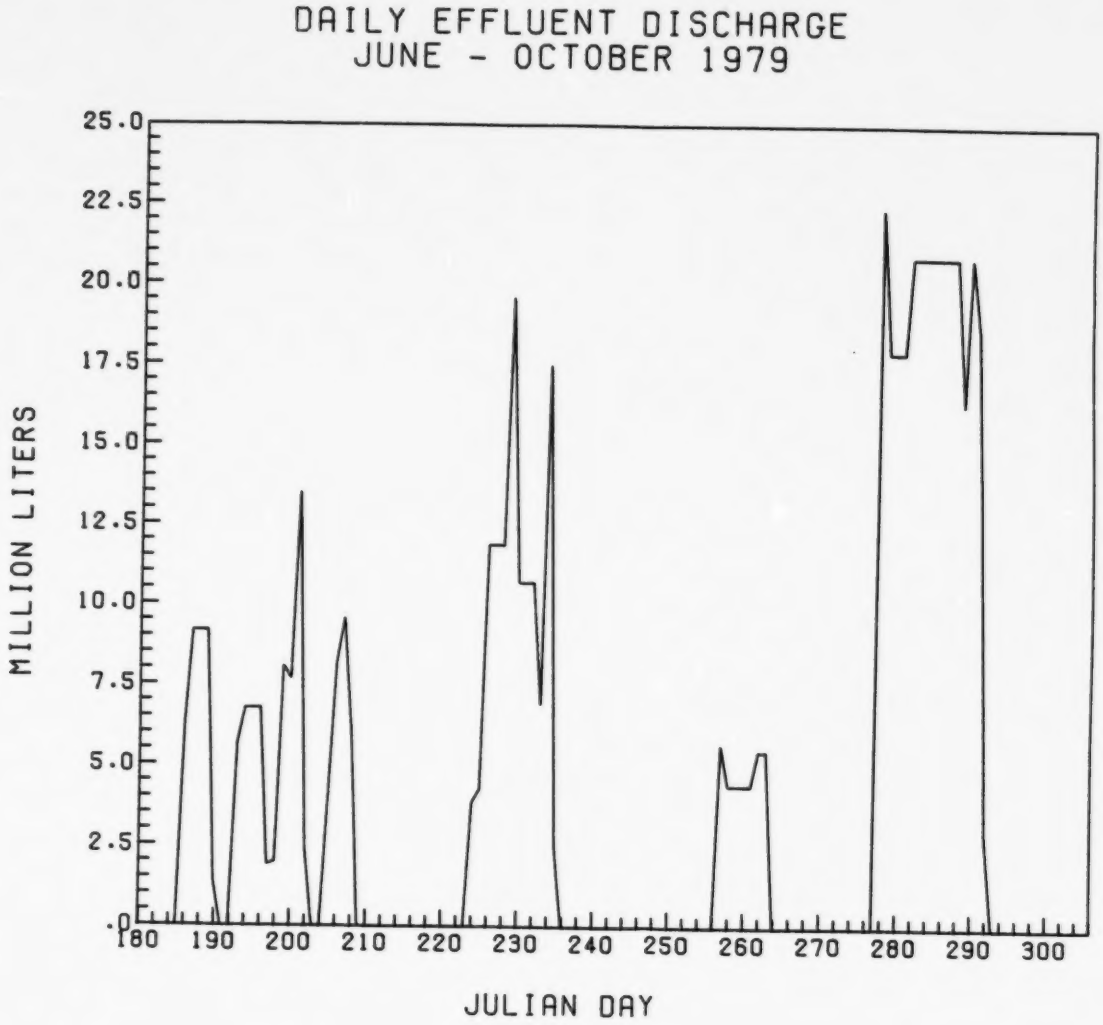


Figure 5. Daily volume of coal ash effluent discharged into the ash pit drain, June to October 1979. The study period is denoted by the solid bar under the x-axis. Data from daily discharge records, Wisconsin Power and Light Co.

centrifuge tube. Following a settling period of several days, the amount of floc layering on top of each sediment sample was measured. No floc was observed in any reference substrate samples.

Data Analysis

Multiple regression and ANOVA were used to detect significant changes in macroinvertebrate abundance related to effluent discharge. Two models were compared. Model I had independent variables for site (APD-1, APD-2 and RRC-2) and time (before and after discharge began). Model II included the above variables plus an independent variable for the site by time interaction. The model providing better fit to the dependent variable (measures of macroinvertebrate abundance and species richness) was determined by calculating the F ratio between the regression sum of squares from the ANOVA of the two models (Draper and Smith 1966). Two alternative hypotheses were tested: (H_0) The site by time interaction was not significant (i.e., non-significant F-ratio) and, thus, any changes in the invertebrate community following the resumption of effluent discharge could not be distinguished from natural variability exhibited at the reference site; (H_1) The site by time interaction was significant (significant F-ratio) and the changes at the experimental sites following resumption of effluent discharge were measurably different from the reference site and could be attributed to exposure to the effluent.

Where F-tests were significant a multiple comparison test (Box et al. 1978) identified individual sites with significant differences in before vs. after macroinvertebrate populations. This test provides 95% confidence intervals for a particular difference in means between two treatments within an ANOVA.

The dependent variables analyzed in this fashion were total macroinvertebrate abundance, Isopoda, Amphipoda and Trichoptera abundances, and the number of taxa. The taxa from the three replicate ponars were pooled for each date. Other variables were calculated as the mean from the three replicate ponars following transformation to natural logs [ln (x+1)] (Elliot 1977). Data collected on the first day of effluent discharge (Day 3 - October 5, 1979) were not included in the analysis because water chemistry data suggested the effluent may not have reached site APD-2 by the time of sampling.

RESULTS

Effect on Stream Habitats

Changes in water chemistry at the experimental sites following effluent discharge, paralleled those reported in earlier studies (Magnuson et al. 1980a). Conductivity, turbidity and total filterable solids (TFR) increased, while pH and alkalinity declined (Table 5). Water temperature, current speed, stream depth and floc (%) in sediments did not show

TABLE 5. MEDIAN (RANGE) OF A SERIES OF PHYSICAL AND CHEMICAL PARAMETERS MEASURED AT SITES APD-1, APD-2 AND RRC-2 BEFORE AND AFTER EFFLUENT DISCHARGE BEGAN

Parameter	APD-1		APD-2		RRC-2	
	Before	After	Before	After	Before	After
Temperature (C)	15 (13-16)	14 (11-16)	13 (12-14)	12 (11-13)	13 (12-13)	10 (8-12)
Current speed (cm/sec)	20 (18-22)	21 (18-25)	18 (17-18)	19 (17-23)	23 (15-30)	20 (15-25)
Mean sample depth (cm)	20 (20)	24 (19-27)	33 (32-33)	32 (31-32)	44 (40-48)	38 (32-42)
Floc in substrate (%)	61 (57-65)	66 (47-68)	22 (0-44)	3 (1-16)	0	0
Conductivity (mhos @ 25C)	467 (433-500)	610 (546-635)	434 (432-436)	570 (455-589)	539 (503-574)	494 (490-537)
Alkalinity (ppm $CaCO_3$)	229 (226-232)	79 (78-86)	203 (202-204)	105 (101-213)	249 (248-249)	245 (244-248)
pH	7.6 (7.6)	7.1 (7.1-7.4)	7.7 (7.6-7.7)	7.4 (7.3-7.5)	7.9 (7.9)	7.9 (7.9-8.0)
Total filterable residue (mg/liter)	3.8 (3.4-4.2)	29.7 (21.1-31.1)	4.5 (4.3-13.5)	28.8 (25.2-31.1)	13.1 (12.7-13.5)	11.4 (9.4-14.7)
Turbidity (JTU)	3.6 (3.3-3.8)	6.3 (5.0-7.6)	4.3 (4.0-4.6)	7.1 (6.3-7.5)	3.1 (3.0-3.2)	3.3 (3.0-3.7)

appreciable changes. At the reference site, stream habitat variables were relatively stable throughout the study period.

Correlations between water chemistry parameters and effluent discharge rate suggested differences in response time at the two experimental sites. At site APD-1 all the water chemistry parameters were significantly correlated with discharge rate (Table 6). In contrast, at APD-2 located further downstream, only turbidity and TFR were significantly correlated with discharge rate. Other parameters (conductivity, alkalinity and pH) were more closely related to the discharge rate of the previous day (Table 6). Thus, while organisms at APD-2 may have been exposed to some precursor of the effluent in the form of increased suspended material on October 5, there was a lag of 1 day in exposure to the chemical components of the coal ash effluent. Figure 6 shows daily values for conductivity and total filterable residue at each site during the study period.

TABLE 6. CORRELATION (R) BETWEEN DAILY EFFLUENT DISCHARGE RATE AND A SERIES OF CHEMICAL AND PHYSICAL PARAMETERS MEASURED AT SITES APD-1 AND APD-2. CORRELATION COEFFICIENTS ARE GIVEN FOR THE RELATIONSHIP BETWEEN EACH STREAM PARAMETER AND EFFLUENT DISCHARGE RATE OF THE SAME DAY AND FOR EACH STREAM PARAMETER AND EFFLUENT DISCHARGE RATE OF THE PREVIOUS DAY FOR SITE APD-2

Variable Correlated with Discharge Rate	Correlation Coefficient (r)		
	APD-1	APD-2	
	Same Day	Same Day	Previous Day
Current speed	0.27	0.23	-0.50
pH	-0.82*	-0.72	-0.61
Conductivity	0.82*	0.69	0.97**
Alkalinity	-0.98**	-0.55	-0.98**
Turbidity	0.90*	0.96**	0.52
Total filterable solids	0.97**	1.00**	0.50
(n)[a]	6	6	5

*Significant difference at the 0.05 level.
**Highly significant difference at the 0.01 level.
[a]Number of days for which observations were compared.

Effect on Macroinvertebrates

Changes in Abundance--

Beginning October 6, the second day of coal ash effluent discharge, macroinvertebrate abundance increased at APD-1 (Figure 6). This was due

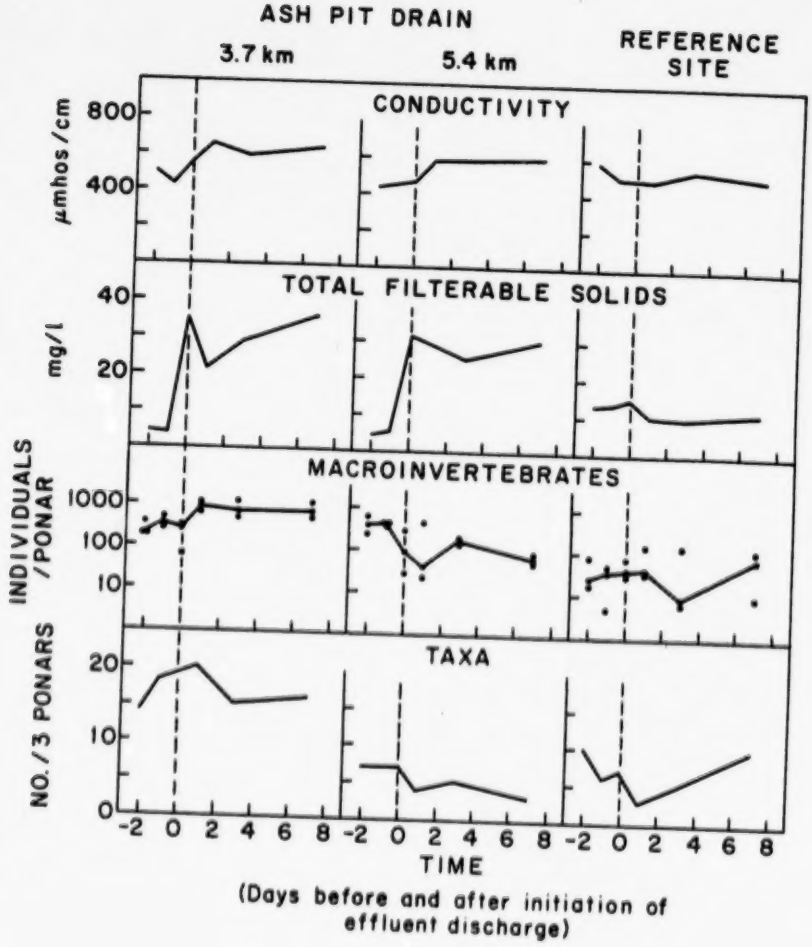


Figure 6. Changes in conductance, total filterable solids, macroinvertebrate density and number of taxa upon resumption of coal ash effluent discharge. Ash pit drain sites 3.7 km and 5.4 km refer to APD-1 and APD-2, respectively. The vertical dashed line indicates the first day of discharge. Macroinvertebrate density (log scale) shows number of individuals in each of three basket samplers indicated by dots; the solid line connects the median. Macroinvertebrate taxa represent pooled value for three samples.

primarily to higher densities of *Asellus racovitzai* and secondarily to *Hyallela azteca* and *Crangonyx* sp. (Table 7). Of the remaining 27 taxa sampled at the site, four were not collected following effluent discharge while nine were present only after discharge began. Most of those taxa were rarely encountered; only *Phryganea* sp., *Oecetis* sp. and *Nemotelus* sp. were collected in more than three ponar samples.

In contrast to the response at APD-1, total macroinvertebrate abundance at APD-2 declined following effluent discharge (Figure 6). This decline began on October 5 when the amount of suspended material increased, but there was no chemical alteration of water quality. Decreases in densities of *Hyallela azteca* and, to a lesser extent, *Asellus racovitzai* accounted for much of the response (Table 7). Of the 12 other taxa collected at this site, only *Cheumatopsyche*, Chironomidae and Hydroptilidae were present in three or more ponar samples. No appreciable differences between before and after populations for these taxa were apparent.

The macroinvertebrate community at the reference site, RRC-2, remained relatively stable throughout the study period (Figure 6). As at the two experimental sites, the dominant macroinvertebrates were *Asellus racovitzai* and *Hyallela azteca*. The remaining community members were comprised of 10 less common taxa (Table 7).

Regression Analysis--

Model II provided better fit to the total macroinvertebrate abundance, Isopoda, Amphipoda and Trichoptera data than did Model I (Table 8). The site by time interaction explained no additional variation of the independent variable, the number of taxa.

Upon further analyses with the multiple comparison test, only a few individual site-specific changes were significant: increases at APD-1 and decreases at APD-2 in total individuals and Amphipoda abundances following effluent discharge (Table 9). Although Model II provided better fit for Isopoda and Trichoptera data, variability within cells apparently masked any site-specific changes. No significant before vs. after differences were measured at RRC-2.

DISCUSSION

The response of benthic macroinvertebrates to resumption of coal ash effluent discharge was not consistent between the two experimental sites. Macroinvertebrate densities increased at APD-1, while at APD-2 numbers declined. Explanations for the lack of consistency between responses can only be speculative. Site APD-1 may provide a more suitable habitat for macroinvertebrate colonization despite receiving a more concentrated effluent. Twice as many taxa were collected at this site than at APD-2. APD-1 is located in an artificially ditched and banked segment of the ash pit drain approximately 30 m downstream from a culvert. Sedges and water grasses are recent (1978) colonizers of previously floc-covered sandy

TABLE 7. COMPOSITION OF PONAR SAMPLES COLLECTED AT THE TWO EXPERIMENTAL SITES, APD-1 AND APD-2, AND AT THE REFERENCE SITE, RRC-1. NUMBERS REFER TO THE MEDIAN (RANGE) ABUNDANCE IN PONAR SAMPLES COLLECTED BEFORE (n=6) AND AFTER (n=12) DISCHARGE BEGAN. ABUNDANCES ARE GIVEN FOR GENERA APPEARING IN MORE THAN THREE PONAR SAMPLES AT A SITE.

Taxon	APD-1		APD-2		RRC-1	
	Before	After	Before	After	Before	After
Isopoda						
Asellus	216(143-342)	555(44-1000)	129(33-239)	25(9-109)	14(0-19)	8(0-45)
Amphipoda						
Crangonyx	1.5(1-5)	5(0-12)				
Gammarus		a				
Hyalella	36(16-56)	84(8-144)	253(194-357)	49(8-310)	19(0-57)	24(1-137)
Insecta						
Trichoptera						
Cheumatopsyche	0(0-9)	2(0-9)	0(0-15)	0(0-6)	0(0-1)	0(0-1)
Hydroptilidae	0(0-2)	1(0-3)		a	0(0-1)	0(0-1)
Oecetis	0( )	0(0-1)	a			
Phryganea		a	a	a		
Polycentropus	a				0(0-2)	0(0-2)
Ptilostomis	0(0-2)	0(0-5)				
Ephemeroptera						
Baetis	a	a				
Caenis	0(0-1)	0(0-1)	a		a	
Callibaetis	0(0-3)	0(0-4)		a	a	a
Hexagenia						
Odonata						
Coenagrionidae		a		a	a	a
Libellula	a					
Tetrogoneuria					a	

TABLE 7. (Continued)

Taxon	APD-1		APD-2		RRC-1	
	Before	After	Before	After	Before	After
Coleoptera						
Agabus lv.	0(0-3)	0(0-1)				
Berosus lv.		a				
Dineutus ad.		a				
Dubiraphia lv.	a					
Dubiraphia ad.			a			
Haliplus lv.	1(0-2)	2(0-9)	a			
Peltodytes ad.	0(0-1)	0(0-1)				
Diptera						
Chironomidae	1.5(0-10)	2(0-14)	0.5(0-1)	0(0-1)	1(0-4)	1.5(0-6)
Chrysops	0(0-1)	0(0-2)				
Hexatoma	0(0-1)	0(0-1)				
Nemotelus	0( )	0.5(0-1)				
Palpomyia	1(0-8)	3.5(0-8)				
Pilaria		a				
Hemiptera						
Belostoma	a					
Corixidae	a	a			0.5(0-1)	0(0-2)
Plea					a	a
Megaloptera						
Sialis		a				
Lepidoptera						
Paraponyx			a	a		a

[a]Present in three or fewer ponar samples.

TABLE 8. COMPARISON OF TWO MODELS DESCRIBING MACROINVERTEBRATE RESPONSE TO RESUMPTION OF COAL ASH EFFLUENT DISCHARGE. GIVEN ARE THE F-RATIOS, COMPARING THE REGRESSION SUM OF SQUARES FROM THE ANOVA OF THE TWO MODELS AND THE LEVEL OF SIGNIFICANCE (NS = NOT SIGNIFICANT) OF THESE F-RATIOS FOR FIVE DEPENDENT VARIABLES

Dependent Variable	F-Ratio (2,9)d.f.	Level of Significance
Total abundance	27.00	$p < 0.001$
Number of taxa	1.61	NS
Isopoda	6.53	$p < 0.05$
Amphipoda	26.69	$p < 0.001$
Trichoptera	4.93	$p < 0.05$

TABLE 9. RESULTS FROM MULTIPLE COMPARISON TEST. PRESENTED ARE THE DIFFERENCE BETWEEN BEFORE AND AFTER MEANS FOR EACH SITE AND THE 95% CONFIDENCE INTERVAL SURROUNDING THAT DIFFERENCE

Dependent Variable	Sample Site	Difference in Means	Confidence Interval
Total abundance	APD-1	-1.00*	±0.91
	APD-2	1.39*	±0.91
	RRC-2	-0.37	±0.91
Isopoda	APD-1	-1.01	±1.74
	APD-2	1.32	±1.74
	RRC-2	-0.10	±1.74
Amphipoda	APD-1	-1.10*	±0.98
	APD-2	1.41*	±0.98
	RRC-2	-0.64	±0.98
Trichoptera	APD-1	-0.66	±0.88
	APD-2	0.35	±0.88
	RRC-2	0.05	±0.88

*Significant difference at the 0.05 level.

substrates. The habitat offered at site APD-1 may provide a refuge for invertebrates (primarily *Asellus racovitzai* and *Hyallela azteca*) disturbed at upstream sites by release of the effluent or entering the coal ash modified habitat from undisturbed sites. Pennak (1978) notes striking aggregations of *Asellus* in streams where velocities are too high to allow further upstream migrations, yet slow enough to allow them to maintain their position.

Site APD-2 is situated in the main channel of the ash pit drain as it flows through a floodplain forest north of the junction with Rocky Run Creek. The stream is subject to wide seasonal fluctuations in water levels and streambank erosion as different channels become formed within the floodplain. As a result, the available stream habitats may provide a naturally less stable environment for invertebrate colonization.

The timing of response was a second difference between the two sites. Although macroinvertebrates at APD-1 were exposed to the coal ash effluent on October 5, no increase in density was observed until the following day. In contrast, at APD-2, decreased abundance occurred on the first day of discharge (October 5) when suspended material increased, but no chemical modifications of water quality -- suggested by altered conductivity or alkalinity -- were measured. The increase in suspended material may have immediately affected the APD-2 community, eliciting a response similar to habitat avoidance. In contrast, at APD-1 the community was unaffected by either the suspended load or chemical alterations of water quality. Population densities did not increase until upstream individuals reached the site and remained there.

In the laboratory drift study (Section 3), macroinvertebrates were associated with the substrate and reduced drift activity when exposed to water and/or sediments contaminated by coal ash effluent. Although the increase in densities at APD-1 may correspond to this response, the lack of consistency with the results from site APD-2 do not make this probable.

The overall impact of resumption of coal ash effluent discharge on the established macroinvertebrate community was not dramatic. The organisms inhabiting the ash pit drain have had to acclimate to periodic disturbances caused by the intermittent pauses in effluent discharge. The detection of a slight response provides some additional evidence for the existence of sublethal stress below the effluent threshold.

SECTION 5

EFFECTS OF THE COAL ASH EFFLUENT ON MACROINVERTEBRATE COMMUNITY STRUCTURE

INTRODUCTION

The effects of environmental contaminants on aquatic communities range from immediate acute toxicity, such as results from spills of highly toxic substances (Crossman et al. 1974), to chronic sublethal impacts which may be more devasting to ecosystems in the long term (Lehmkuhl 1979). Sublethal impacts are difficult to evaluate through monitoring of individual physical and chemical parameters, because the concentrations of toxicants that induce chronic stress are often ill defined. In addition, ecosystems are often subjected to a variety of stresses operating simultaneously and, perhaps, synergistically.

For these and other reasons, monitoring of biological responses to pollutants has become an integral part of water quality evaluation procedures. Aquatic organisms respond to the environment in an integrated fashion, making them better indicators of environmental stress than chemical and physical parameters (Cairns et al. 1973). Aquatic macroinvertebrates possess several attributes which enhance their use as biological indicators (Cover and Harrell 1978). These include limited mobility, a relatively long life span leading to responses which are a reflection of recent conditions, occupation of several trophic positions as well as being important links in aquatic food webs, and exhibition of a range of known tolerance limits to different environmental factors.

Previous reports have documented impacts of the coal ash effluent discharged by the Columbia Electric Generating Station on the macroinvertebrate community inhabiting the receiving stream. The effects were measured temporally--through comparisons of pre- and post-operation community structure--and spatially--through examination of distributions along a gradient of effluent strength (Magnuson et al. 1980a, Forbes et al. 1981).

This section will describe changes in macroinvertebrate community structure at one highly impacted site within the coal ash drainage system. An additional year of data (1980) allowed documentation of the following sequence of events: (1) initial decline of intolerant taxa following effluent discharge in 1975; (2) disappearance of most taxa in 1977; and (3) subsequent partial recovery in 1980. Analysis was based on examination of

responses of individual taxa and an analysis of changes in community structure. Details on this data set can be found in Magnuson et al. (1980).

METHODS

Macroinvertebrate Samplers

Artificial substrate samplers were used to investigate the macroinverterate community inhabiting site APD-1 of the ash pit drain. The advantages of these samplers are the elimination of substrate differences as effects between sites and over time, ability to retrieve quantitative data from hard to sample sites, ease of sample processing, and higher precision than other methods (Weber 1973). Disadvantages include the length of exposure time, vulnerability to vandalism and dislodgement, inability to measure effects of alteration of natural substrates, and development of a community which may not reflect prior conditions (Weber 1973).

Two types of artificial substrates were used. Basket samplers (Mason et al. 1970) were used during the summers of 1974, 1975, and 1980 (Table 10). These consisted of closed cylinders 20 x 30 cm constructed of chicken wire and filled with 4.5 kg of limestone rocks. At the downstream ash pit drain site, three baskets were suspended approximately 10 cm above the stream sediments at mid-channel. Following a colonization period of approximately 4 weeks, the contents of each basket were shaken into a 1-mm mesh dip net and then preserved in 70% ethanol. Macroinvertebrates were

TABLE 10. DATES SHOWING INTERVALS FOR MACROINVERTEBRATE COLONIZATION OF ARTIFICIAL SUBSTRATE SAMPLERS IN THE ASH PIT DRAIN. THE NUMBER OF SAMPLERS RETRIEVED IS SHOWN IN PARENTHESES

Sampler Type	Year			
	1974	1975	1977	1980
Basket	-	16 May-13 June (3)		15 May-13 June (3)
	29 May-1 July (2)	13 June-9 July (3)		13 June-16 July (3)
	1 July-30 July (1)	9 July-7 Aug. (3)		16 July-8 Aug. (3)
	30 July-27 Aug. (3)	7 Aug.-5 Sept. (3)		8 Aug.-10 Sept. (3)
	27 Aug.-24 Sept. (3)	5 Sept.-30 Oct. (3)		
Modified Dendy			26 May-2 June (3)	2 June-9 June (7)
			1 Sept.-9 Sept. (3)	

later hand-sorted and all individuals counted. If more than 2.5 h were required to sort the first quarter of a sample, subsamples were analyzed (Magnuson et al. 1980a). With the exception of a few taxa which were identified to family, identification was to the genus level using keys designed by Hilsenhoff (1975). Identification of some taxa was verified by Dr. W. Hilsenhoff, University of Wisconsin-Madison.

A modified multiplate Hester-Dendy artificial substrate (Hester and Dendy 1962) was used to compare macroinvertebrate populations upstream (APD-3) and downstream (APD-1) of the effluent in the ash pit drain in 1977 and 1980. Site locations are shown in Figure 1. Colonization periods are listed in Table 10. The modified Dendy consisted of a Tuffy® scrub ball held between two 8-cm^2 masonite plates by an eyebolt. Samplers were suspended by floats 20 cm above stream sediments and anchored by cement blocks. Three to seven samplers were placed 1 dm apart longitudinally at random locations across the width of the stream. After a 1-week colonization period, samplers were retrieved, placed in freezer containers, and preserved in 70% ethanol. For processing, sample contents were washed through 70 µm mesh to concentrate organisms and to remove fine silt. Macroinvertebrates were sorted, counted, and identified as previously described.

Comparison of Samplers

The macroinvertebrate taxa colonizing basket and modified Dendy artificial subtrates in June 1980 were similar (Table 11). Eleven of the 20 taxa collected colonized both sampler types. These included most of the major taxa based on abundance. Ranks for individual taxa, based on relative abundance, were also similar for the two sampler types. The Spearman rank correlation coefficient (Siegel 1956) comparing ranks by abundance of each taxon, collected by baskets and Dendy samplers, was 0.626, significant at $p < 0.01$.

Three taxa--caddisflies (*Cheumatopsyche* spp. and *Hydropsyche* spp.) and Coenagrionidae damselflies--colonized only basket samplers in June 1980. These taxa have previously colonized modified Dendy samplers at other sites in the ash pit drain (Magnuson et al. 1980a). Modified Dendy samplers were colonized by six taxa not observed in baskets. These taxa occurred at low abundances (means of 0.1 to 0.4 individuals per sampler).

Although basket samplers collected more individuals due partly to their greater surface area available for colonization, taxonomic richness was similar between sampler types. The medians and range of number of taxa collected per basket and Dendy were 9 (6 to 11) and 9 (8 to 14), respectively. Mason et al. (1973) also observed similar abundances and macroinvertebrate taxa colonizing basket and multiplate samplers, although a few species showed distinct preference for one sample type.

TABLE 11. COMPARISON OF MACROINVERTEBRATE TAXA COLONIZING BASKET AND MODIFIED DENDY SAMPLERS AT SITE APD-1. COLONIZATION PERIODS WERE MAY 15 TO JUNE 13 (BASKETS) AND JUNE 2 TO 9 (DENDY) IN 1980. SAMPLE SIZES WERE 3 AND 7 FOR BASKETS AND DENDY SAMPLERS, RESPECTIVELY. RANKS ARE BASED ON ABUNDANCE

Macroinvertebrate Taxon	Number per Sampler		Rank	
	Basket Sampler	Modified Dendy	Basket Sampler	Modified Sampler
Taxa in Both Sampler Types				
Asellus racovitzai	205	127	1	1
Hyallela azteca	58	51	2	2
Peltodytes lv.	26	3.7	3	5
Crangonyx	5.7	9.0	4	3
Gammarus pseudolimnaeus	3.7	7.6	5.5	4
Limnephilus	2.0	0.7	7	7
Hydroptilidae	1.3	0.6	8.5	8.5
Chironomidae	1.3	1.0	8.5	6
Haliplus lv.	0.3	0.6	13	8.5
Helodidae lv.	0.3	0.1	13	14.5
Tropisternus lv.	0.7	0.1	11	14.5
Taxa in One Sampler Type				
Cheumatopsyche	3.7		5.5	
Coenagrionidae	1.0		10	
Hydropsyche	0.3		13	
Asynarchus		0.4		10.5
Palpomyia		0.4		10.5
Caenis		0.1		14.5
Triaenodes		0.1		14.5
Liodessus lv.		0.1		14.5
Cauliodes		0.1		14.5

Data Analysis

Various measures were used to compare macroinvertebrate community structure in the pre-operational year 1974 and post-operational years of 1975, 1977, and 1980. The responses of individual taxa were measured as changes in occurrence and abundance throughout the study period. Community responses were evaluated through a series of indices including number of individuals, number of taxa, Shannon Weaver diversity ($\bar{H}$) and evenness (e) (Pielou 1969) (Equation 1).

$$\bar{H} = \sum_{i=1}^{s} p_i \log_2 (p_i) \quad \text{and} \quad e = \frac{H}{\log s}, \tag{1}$$

where s is the total number of taxa and p_i is the proportion of total individuals in the ith taxa. All indices were calculated from mean abundances determined from the contents of replicate basket samplers collected on the same date. A Friedman two-way ANOVA, a measure of the effect of K treatments upon the ranks of a response, was used to examine differences in index values between years (Siegel 1956).

Diversity indices have long been used as biological indicators of water quality and measures of community response to pollutants (Wilhm and Dorris 1968). However, interpretation of pollutant impacts using diversity indices alone without understanding the ecology of the community can lead to misleading conclusions (Hynes 1970, Hocutt 1975). Although environmental conditions may vary, diversity indices may equate pollution tolerant communities with more typically clean water communities (Godfrey 1978).

RESULTS

Community Composition

Presence/Absence--

The presence of each major macroinvertebrate taxon artificial substrates collected at site APD-1 in June and August in 1974, 1975, 1977 and 1980, is indicated by solid lines in Figure 7. Data for 1977 were based on colonization of modified Dendy type samplers; other years are from basket samplers. In Figure 7 the presence of a particular taxa in months other than June or August is indicated by a dashed line.

In 1975, only two pre-operation taxa did not return (Tabanidae and *Stenonema* sp.). One genus, the amphipod *Crangonyx* sp., first appeared after pumping began. The lack of organisms in 1977 is striking. During June, only a few individuals of the isopod, *Asellus racovitzai*, the amphipod *Hyallela azteca*, and Chironomidae were found. In August 1977, no organisms colonized Dendy samplers at site APD-1. By 1980 recovery of most of the

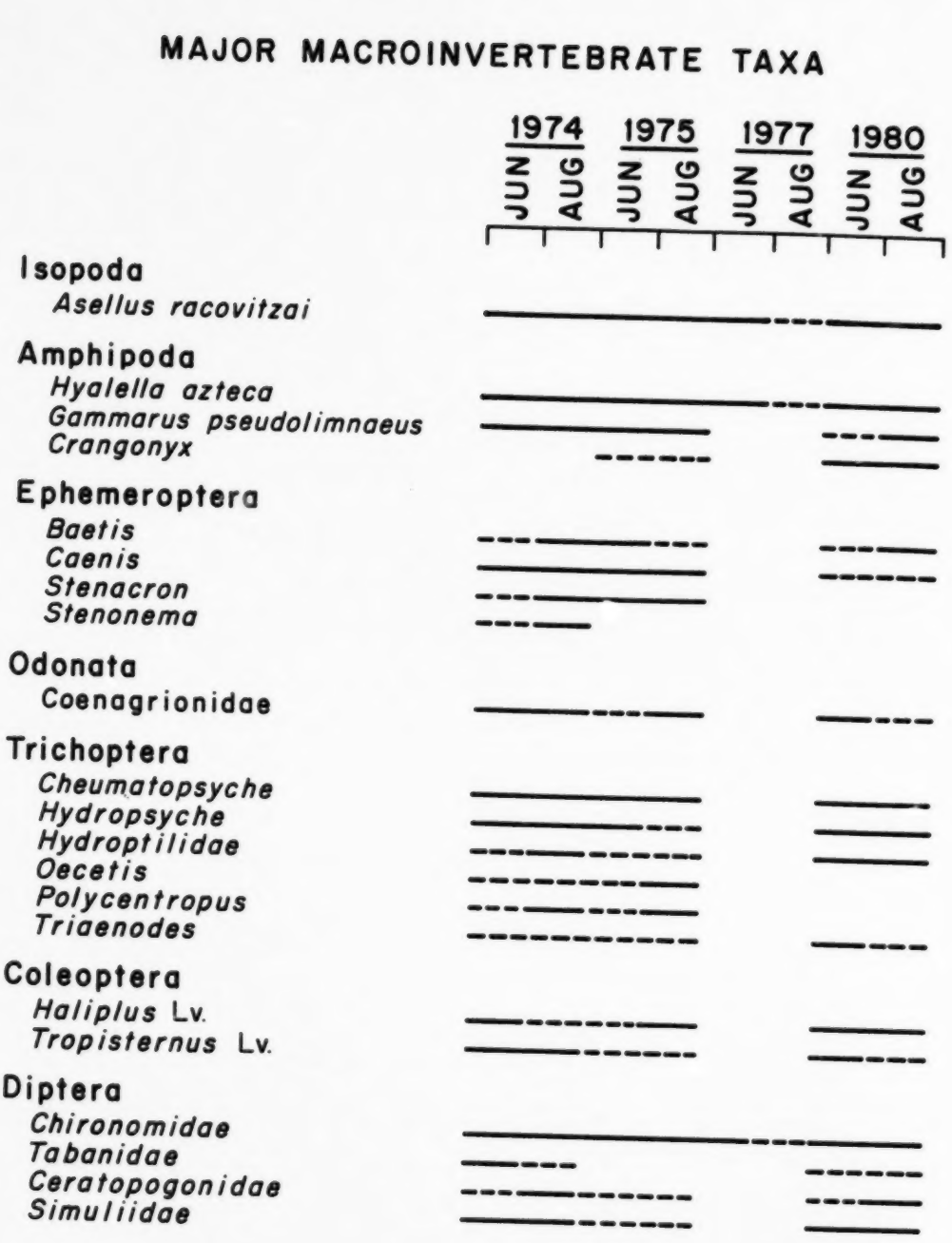


Figure 7. Occurrence of major macroinvertebrate taxa in artificial substrate samplers collected at APD-1 in June and August 1974, 1975, 1977, and 1980. A solid line indicates presence during the month represented; a dashed line indicates presence during a month other than June or August.

major taxa was evident. Only two mayflies, *Stenonema* sp., and *Stenacron* sp. and two caddisflies, *Oecetis* sp. and *Polycentropus* sp. did not return.

Relative Abundance--

Although no major differences in the presence of taxa in 1974, 1975 and 1980 samples were apparent, changes occurred in the relative and absolute abundances of several groups (Figure 8). The pre-operation 1974 community was dominated numerically by Hydropsychid caddisflies, mainly of the genus *Cheumatopsyche*, with lesser numbers of *Hydropsyche*. Chironmidae were the next important group numerically.

In 1975, community composition in June and July was similar to that of 1974 (no data were collected in May 1974). By August, however, several taxa, notably *Cheumatopsyche* spp., *Hydropsyche* sp. and Chironomidae, had disappeared. Other taxa not present in August 1975 samples include *Gammarus pseudolimnaeus* and *Stenocron*. Abundances of *Asellus racovitzai* and *Hyallela azteca* increased. The effects of the coal ash effluent were thus not detected until 4 months after discharge began in April 1975 (Magnuson et al. 1980a).

In 1980, 5 yr after effluent discharge was initiated, the community was dominated by *Asellus racovitzai* and *Hyallela azteca*, two of the three taxa colonizing modified Dendy samplers at site APD-1 in 1977. Formerly dominant taxa *Cheumatopsyche* spp. and *Hydropsyche* sp. returned, but at greatly reduced abundances.

Indices of Community Structure--

Monthly values for four indices of community structure at site APD-1 are shown in Figure 9 for 1974, 1975 and 1980. On a monthly basis, Shannon Weaver diversity and evenness show general, but not appreciable, declines from 1974 to 1980. The numerical dominance of the 1980 community by *Asellus racovitzai* (66 to 83% of total individuals) probably caused these two indices to decrease.

Number of taxa was similar for all 3 yr for May, June, July and August. Although a more substantial difference is apparent in September between 1974 and 1975, no data was collected in September 1980 for additional comparison.

While total abundances from May to July were similar between years, late summer abundances were dramatically different. Populations exceeded 2,000 individuals per basket sample in August 1974. This late summer increase in total abundance did not occur in 1975, when the first effects of coal ash effluent discharge were observed. A similar pattern of late summer increase took place in 1980, but total abundance was < 50% of 1974 values. None of the differences between years for these indices were significant based on the Friedman two-way ANOVA.

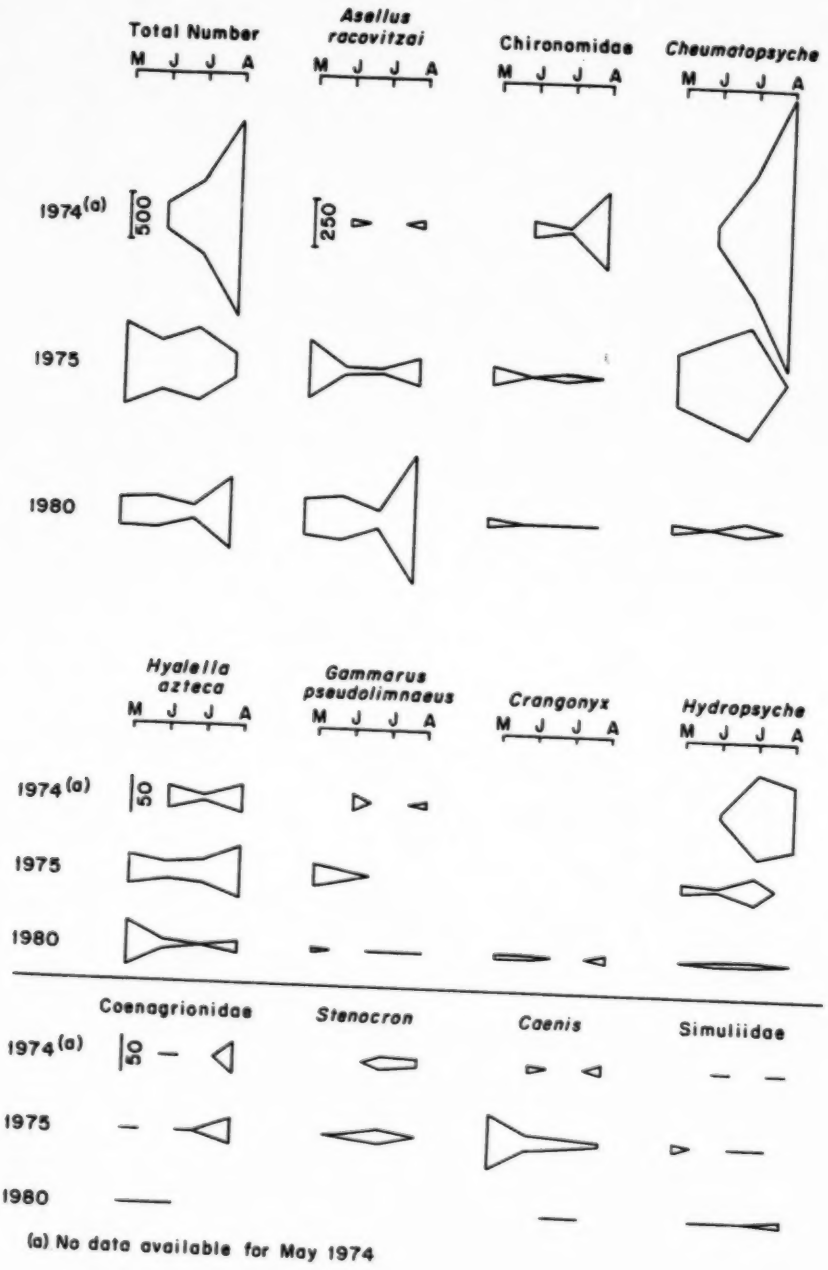


Figure 8. Total abundance and abundances of selected taxa during the summer months of 1974, 1975, and 1980 in basket samplers. Note difference in scale between total number and individual taxa.

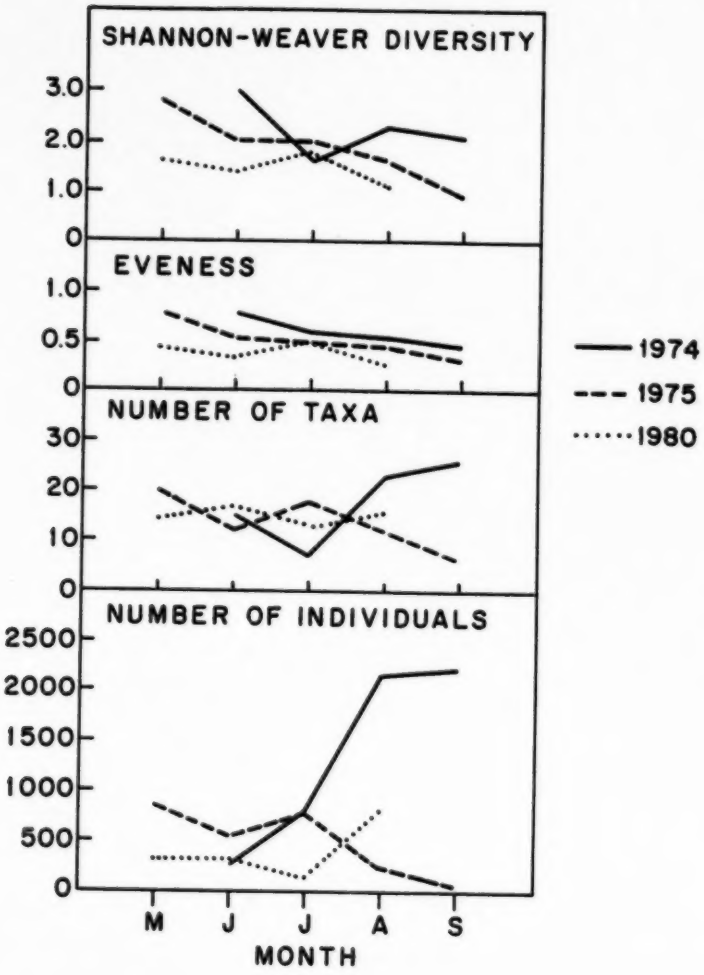


Figure 9. Shannon-Weaver diversity, evenness, number of taxa and number of individuals at site APD-1 during the summer months of 1974, 1975, and 1980.

Upstream-Downstream Comparisons

The results of the June 1980 replication of the 1977 sampling, comparing colonization of substrates at the upstream (APD-3) and downstream (APD-1) sites in the ashpit drain, are shown in Figure 10. While there were dramatic differences between the two sites in total macroinvertebrate abundance and number of taxa in 1977, no substantial differences in these parameters were apparent in 1980.

Evidence for a decline in environmental stress imposed by the coal ash effluent in 1980 was provided by evaluation of conductivities measured at the upstream and downstream sites in 1977 and 1980. Forbes et al. (1981) derived a biological response threshold based on effluent conductivity from the series of laboratory and field studies summarized in Table 12. Ash pit drain sites receiving concentrations of coal ash chemicals exceeding 1000 mhos conductance were unsuitable for macroinvertebrate colonization (Forbes et al. 1981). This relationship was not meant to imply elevated conductivity as a cause of the observed responses; rather, it provided a chemical indicator of effluent concentrations harmful to invertebrates.

As shown in Figure 10, effluent concentrations at site APD-1 clearly exceeded the habitable limit. Conductivity was nearly 2500 mhos, significantly higher than the 1000 µmho response threshold. The lack of invertebrates mirrors the severity of environmental stress. When effluent concentrations fell below the 1000 µmho threshold in 1980, total abundance and number of taxa were similar to upstream values. This result supports the ability of the conductivity threshold to predict the severity of environmental stress in stream habitats altered by coal ash chemicals discharged by the Columbia Generating Station.

DISCUSSION

The following sequence of macroinvertebrate responses to habitat modification by the coal ash effluent was observed: (1) decline in total abundance and number of taxa 4 months after effluent discharge began; (2) near total disappearance of all macroinvertebrates in 1977; and (3) recovery of most taxa in 1980. The macroinvertebrate community in 1980, while similar in taxonomic composition to the 1974 pre-operation community, had experienced significant shifts in absolute abundance as well as the relative abundances of individual taxa. The resulting community was characterized by lower total abundances overall and domination by *Asellus racovitzai*. The intensity of community response was related to effluent concentration; when concentrations exceeded the conductivity response threshold established by Forbes et al. (1981), macroinvertebrate populations were severely reduced.

Environmental stress can have a selective or non-selective impact on aquatic communities (Hocuttt 1975). A selective stress, such as organic pollution generally results in a decline in the number of taxa and increases in abundance of tolerant forms. A non-selective stress, such as scouring or sedimentaiton, will reduce the number of individuals but not necessarily the number of taxa. According to Hocutt (1975), the initial reduction in the

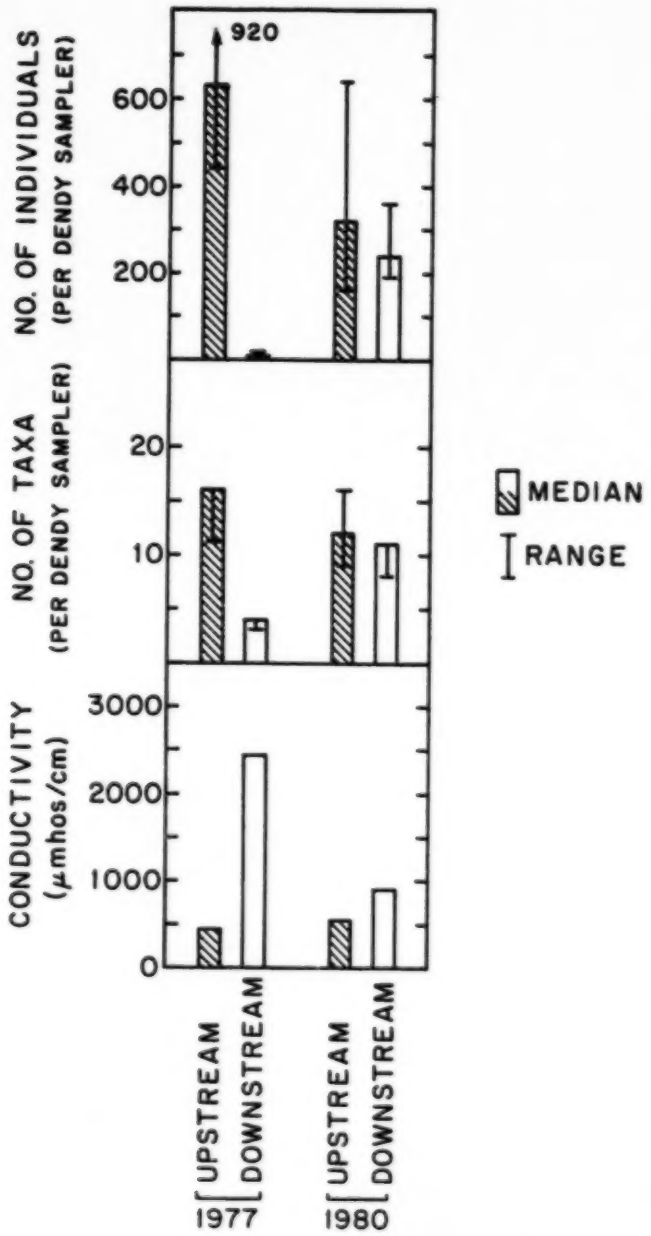


Figure 10. Comparison between conductivity, macroinvertebrate abundance and number of taxa at upstream APD-3) and downstream (APD-1) sites in the ash pit drain in 1977 and 1980.

TABLE 12. SUMMARY OF EXPERIMENTAL STUDIES INVESTIGATING RESPONSES TO COAL ASH EFFLUENT. LISTED ARE THE RESPONSES INVESTIGATED, WHETHER THESE RESPONSES WERE MEASURED ACROSS AN EFFLUENT GRADIENT, THE DIRECTION OF RESPONSE, THE CONDUCTIVITY LEVEL AT WHICH THE RESPONSE WAS DETECTED, AND THE CONDUCTIVITY INTERVAL BRACKETING THE RESPONSE THRESHOLD. STUDIES CONDUCTED AT ONE EFFLUENT CONCENTRATION OR FOR WHICH NO THRESHOLD INTERVAL COULD BE DERIVED ARE DESIGNATED BY A N/A

Year(s)	Biological Response Investigated	Conductivity Gradient	Response to Coal Ash	Conductivity Level	Response Threshold	Reference
1977	Survival of crayfish caged on-site	Yes	None	1800	1800	a,b,c
	Metabolic rate of caged crayfish	Yes	Reduced	1500	730-1500	a,b,c
	Body burden toxic elements in caged crayfish	Yes	Generally increased	730	n/a	a,b,c
	Hatching success and survival northern pike eggs and sac fry	Yes	Reduced	1160	520-1160	d
1977-1978	Survival of *Asellus* in laboratory bioassay	Yes	None	1200	1200	a,b,c
1978	Survival of adult *Gammarus* in laboratory bioassay	Yes	None	1900	1900	a,b,c
	Survival of juvenile *Gammarus* in laboratory biossay	Yes	Reduced	1900	1100-1900	a,b,c

TABLE 12. (Continued)

Year(s)	Biological Response Investigated	Conductivity Gradient	Response to Coal Ash	Conductivity Level	Response Threshold	Reference
1978-1979	Leaf decomposition and microbial colonization	No	Reduced	900	n/a	d
1979	Macroinvertebrate drift in laboratory streams	No	Reduced	500	n/a	e,f

[a]Magnuson et al. (1980a).
[b]Forbes et al. (1981).
[c]Harrell (1978).
[d]Magnuson et al. (1980b).
[e]Webster et al. (1981).
[f]Section 3.

numbers of taxa and individuals due to sublethal or toxic stress is followed by a slow adaptation and recovery to a stable, but submarginal environment dominated by a few highly productive species.

The coal ash effluent discharged from the Columbia Electric Generating Station elicited changes in macroinvertebrate community structure similar to those described for non-selective and sublethal/toxic stresses. Over the 7-yr period of observation, the coal ash effluent imposed a variety of chemical (higher concentrations of dissolved and suspended material, occasionally harmful concentrations of dissolved metal elements) and physical (habitat reduction due to smothering of stream sediments by a chemical floc) stresses. The severity of environmental stress changed during the study period, reaching a peak in 1977 when the most devastating effects of the coal ash effluent were documented (see Section 6). Recovery was observed following reductions in habitat stress, but with a change in community structure.

This shift from a community dominated by hydropsychid caddisflies (1974-75) to one dominated by the isopod *Aselluls recovitzai* (1980) was one of the most dramatic responses documented at site APD-1. Hydropyschid caddisflies function as collector-filterers, constructing nets which retain algae, detritus, and animals carried by stream currents (Merritt and Cummins 1978). The accumulation of a chemical floc coating stream substrates reduced the available habitat for caddisfly larvae and probably played an important role in their disappearance during 1977. Although apparently tolerant of organic loading (Hilsenhoff 1982), the Hydropsychidae are fairly intolerant of toxic pollutants (Roback 1974). Continued exposure to coal ash chemicals through 1980 may have been sufficient to prevent total recovery of these insects even though floc deposits were significantly reduced.

In contrast, densities of *Asellus recovitzai* increased at site APD-1. Numerous individuals were collected in 1979 ponar samples (Section 5) and 1980 basket samplers. The location of site APD-1 below a culvert may represent a point where stream velocity is favorable for the development of isopod aggregations (Pennak 1978). Substrate modification may not have been as detrimental to *Asellus* as to the Hydropsychidae. Isopods are scavengers, consuming dead and injured animals and green and decaying leaves, grass and aquatic vegetation (Pennak 1978).

The tolerance of *Asellus* to organic loadings has been noted (Aston and Milner 1980, Hilsenhoff 1982), and this genus has been used as an indicator of organic pollution in Europe (Hynes 1970). Literature on tolerance to toxic pollutants is sparse. In a laboratory study, Fraser (1980) increased the tolerance of *Asellus aquaticus* to Pb by exposing intolerant animals from an unpolluted site to low levels of Pb. The demonstrated tolerance of isopods to other types of pollutants may justify extension to coal ash chemicals. *Asellus racovitzai* was one of three invertebrate taxa collected (in small numbers) at site APD-1 in 1977 when effluent concentrations were highest and environmental stress most severe.

Although the structure of the macroinvertebrate community inhabiting the ash pit drain typifies an organically polluted condition (Hilsenhoff 1982), it is unlikely that organic enrichment is the cause of the observed responses. Both crayfish and northern pike eggs and sac fry have survived long-term *in situ* caging experiments (Magnuson et al. 1980a, b) indicating diurnal oxygen depletion is not significant. Signs of over-fertilization were not apparent; visible macrophyte and algal growth were low, although occasional clumps of floc colonized by periphyton were observed. Most likely, the ashpit drain macroinvertebrate community is a reflection of the source of colonizers, an enriched agricultural drain.

The actual cause and effect mechanisms by which the coal ash effluent impacted macroinvertebrate populations were investigated in a series of studies conducted between 1977 and 1979 (Table 12). As summarized by Forbes et al. (1981), the only evidence for acute toxicity was from bioassays using more sensitive early life stages. The major impacts of the coal ash chemicals may have been through sublethal effects on physiology and behavior resulting from accumulations of trace metals in body tissues and/or inadequate food supply (Forbes et al. 1981, Forbes and Magnuson 1980) (Section 3).

Results from other studies have demonstrated a variety of sublethal effects of trace elements on aquatic organism, including impacts on behavior, fecundity, longevity, and reproduction (Lehmkuhl 1979). Reductions in activity of crayfish were observed following exposure to sublethal concentrations of Cd (Maciorowski et al. 1977). Chironomids exposed in the laboratory to sediments contaminated with Cd, Cr and Zn exhibited avoidance responses which increased in intensity with increasing Cd and Zn levels (Wentsel et al. 1977a). In a separate experiment chironomids suffered reductions in survival and growth (Wentsel et al. 1977b). Sublethal chronic exposure to Cu reduced the life span and brood size of *Daphnia magna* (Winner and Farrell 1976). Sublethal Cu concentrations also reduced brood size in other *Daphnia* species, completely halting reproduction in the three most sensitive species.

Effects on physiology, measured as declines in metabolism, can also be attributable to inadequate food supply. Forbes and Magnuson (1980) documented low decomposition rates of leaves in the ash pit drain, suggesting reduced food quality. A visual inspection indicated that food quantity was also low (Forbes et al. 1981). A decline in oxygen consumption has been reported for some intertidal invertebrates in response to starvation (Newell 1973).

It was difficult to attribute the observed changes in community structure to any one of the potential environmental stresses imposed by the coal ash effluent. Impacts of altered water chemistry could not be separated from the physial effects of habitat loss due to accumulations of a chemical floc as the intensity of stress imposed by these two factors varied in a similar fashion during the study period (Section 6). In addition, hypotheses of acute and sublethal impacts of the effluent were supported by the results of the laboratory and field manipulations.

SECTION 6

EVALUATION OF ENVIRONMENTAL STRESS IN THE COLUMBIA COAL ASH DRAINAGE SYSTEM

INTRODUCTION

Environmental stress in the coal ash drainage system of the Columbia Electric Generating Station was evaluated using a combination of biological and chemical indicators. Severely stressed sites were characterized by a substantially reduced macroinvertebrate fauna and by coal ash effluent concentrations exceeding the biological response threshold of 1000 μmho conductivity (Forbes et al. 1981, Magnuson et al. 1980a). A temporal variation in the intensity of environmental stress was detected at site APD-1 over the 7-yr study period. A partial recovery was documented 3 yr after a depauperate fauna was observed (Section 5).

Variations in the intensity of environmental stress can be attributed to changes in generating station procedures, including methods of coal and effluent treatment and rate of effluent discharge. This section will describe activities influencing effluent concentration (indicated by conductivity) and occurrence of floc deposits. The latter qualitative variable is included as a measure of substrate modification, an important influence on macroinvertebrate distributions. The close correspondence between estimates of environmental stress based on effluent conductivity and substrate modification and the estimates based on biological data will be discussed.

INFLUENCE OF GENERTING STATION ACTIVITIES

Conductivity

The major sources of conductivity in the effluent were the $NaHCO_3$ (1975-78) and NH_4HSO_4 (1979-80) added to the pulverized coal to increase the efficiency of the electrostatic precipitator. The transport of these compounds with the fly ash through the settling ponds and into the ashpit drain, elevated conductance values in proportion to the concentration of the effluent. Thus, the main generating station activities influencing conductivity values were the frequency and rate of discharge (Table 13).

The relationship is shown in detail in Figure 11, which presents plots of frequency of discharge, (percentage of days in the year when effluent was released), the mean and range of discharge rate and the mean and range of

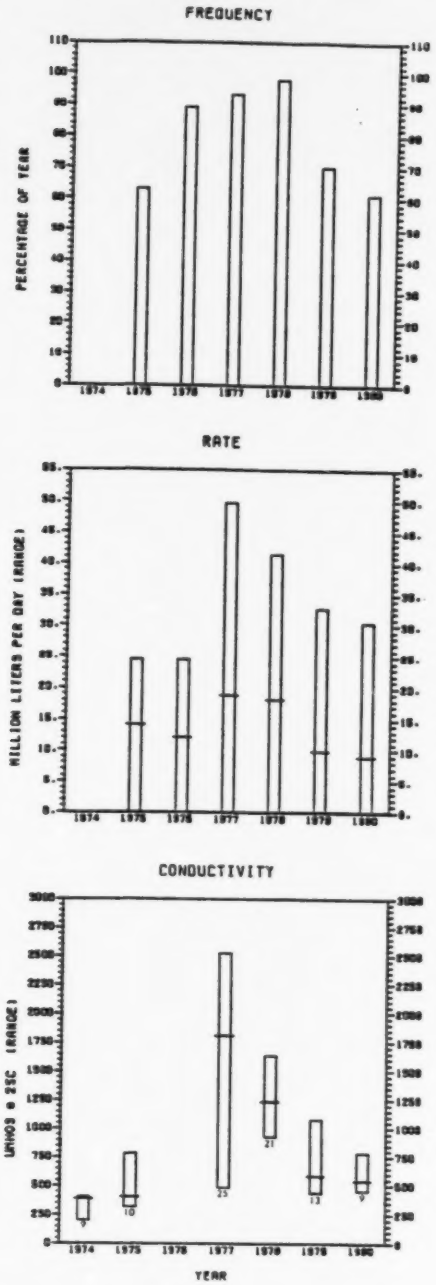


Figure 11. Conductivity, effluent discharge rate and frequency of discharge between 1974 and 1980. Bars and horizontal lines represent range and mean for discharge rate and range and median for conductivity. Number of conductivity observations are shown under bars.

TABLE 13. SUMMARY OF OBSERVATIONS ON CONDUCTIVITY AND EXTENT OF FLOC DEPOSITS AT SITE APD-1 AND GENERATING STATION ACTIVITIES POTENTIALLY INFLUENCING ASH PIT DRAIN HABITATS. DISCHARGE RATES ARE MEAN DAILY DISCHARGE FOR YEAR; CONDUCTANCE IS MEDIAN FOR YEAR

	Station Operation				Indicators	
Year	Discharge (10^6 liter/day)	Coal Treatment	pH Control	Floc Removal	Conductance (μmhos)	Floc Deposits
1975	14	None	H_2SO_4	No	400	(No observation)
1977	19	$NaHCO_3$	H_2SO_4	No	1800	Extensive
1979	10	NH_4HSO_4	H_2SO_4	Yes	600	Diminished
1980	9	NH_4HSO_4	CO_2	Yes	500	Rare

conductivity observations from 1974 through 1980. There was no systemataic monitoring of conductivity; the data represent all the available information for site APD-1. The highest conductivity values (median 1805 mhos) were measured in 1977 when discharge volume per day and frequency of discharge were at or near peak. Only five of 25 conductivity observations made during that year were < the 1000 μmhos biological response threshold. By 1979 and 1980, when the frequency and rate of discharge had declined, conductivities rarely exceeded the 1000 μmhos threshold.

Floc Deposits

The extent of floc deposits varied in a fashion similar to that of conductivity throughout the study period. The thick layers of floc which accumulated on stream substrates in 1977 were substantially diminished by 1979 and were rarely observed in backwater pools in 1980.

The reductions in floc formation by 1979 were also associated with declines in effluent discharge (Table 13). Removing accumulated floc in the effluent ditch immediately below the discharge point was an important factor because it reduced the downstream transport of precipitated materials. Before 1979, H_2SO_4 was added to achieve effluent pH control; after 1979 CO_2 bubbling was used to control pH. This change in methods may also have reduced precipitation of the dissolved metals which formed the floc (R. Perry, Personal communication, Wisconsin Power and Light Co., June 1980).

CHEMICAL AND BIOLOGICAL INDICATORS

Macroinvertebrate community structure at APD-1 reflected the severity of environmental stress predicted by the chemical indicators (Table 14). In 1977 when conductivities were predominantly above threshold and floc deposits were extensive, only a few macroinvertebrates colonized modified Dendy samplers in June; no individuals were collected in September (Manguson et al. 1980a). The chemical and biological indicators emphasized the severely stressed conditions at APD-1 during that year. When conductivities declined below threshold and floc deposits diminished in 1979-80, many macroinvertebrate taxa recolonized the previously depauperate site. This recovery was first observed in the fall of 1979 (Section 4) and documented in 1980 with the same sampling designs used in previous years (Section 5).

TABLE 14. ESTIMATES OF SEVERITY OF ENVIRONMENTAL STRESS AT APD-1 IN 1975, 1977 AND 1980 BASED ON CHEMICAL AND BIOLOGICAL INDICATORS.

		Chemical Indicators		Biological Indicator
Year	Environmental Stress	Conductance (µmhos)	Floc Deposits	Macroinvertebrate Community Structure at APD-1
1975	Low	400	(No observation)	Late summer declines in intolerant taxa
1977	Severe	1800	Extensive	Disappearance of nearly all individuals
1980	Low	500	Rare	Re-establishment of many taxa, *Asellus* now numerically dominant

Comparisons of macroinvertebrate abundance and species richness at APD-1 and at the ashpit drain site upstream of the effluent (APD-3) in June 1977 and 1980 were previously described (Section 5, Figure 10). The dramatic difference in between-site number of taxa and individuals in 1977 when conductivites were 2500 µmhos at APD-1, disappeared in 1980 when conductivities were below threshold and approached background levels.

Although several taxa were able to recolonize the previously severely disturbed APD-1 site by 1980, community composition differed from the preoperation (1974) community (Section 5). The tolerant isopod species--*Asellus racovitzai*--became numerically dominate in 1980. This species was present in 1974 prior to effluent discharge but at much lower abundances. This shift in dominants from *Cheumatopsyche* spp. to *Asellus racovitzai* suggests a continued, sub-acute disturbance from exposure to the coal-ash chemicals below the biological response threshold. Results from three

studies demonstrated possible effects on macroinvertebrates at sub-threshold effluent concentrations: (1) reduction in food quality through lowered microbial colonization and decomposition rates of leaves (Forbes and Magnuson 1980); (2) reduced invertebrate drift activity (Section 3); and (3) periodic disturbance due to the intermittent nature of effluent discharge (Section 4).

DISCUSSION AND SUMMARY

The intensity of environmental stress varied substantially over the 7-yr study period at site APD-1. The cause of this variability was attributable to a series of generating station activities influencing both the quantity and quality of effluent discharge. Discharge rate and frequency were closely related to effluent conductivity. Although the extent of floc deposits was also linked to discharge rate, the removal of accumulated floc from the upper-most stretch of the drainage ditch probably contributed greatly towards reducing downstream accumulations.

The importance of efficient coal ash waste handling procedures has been emphasized in other studies. Cherry et al. (1979) report recovery of most invertebrate groups in the swamp drainage system of a power plant in Georgia following construction of an efficient retaining basin system. Invertebrate densities had been reduced following periodic perturbations of heavy ash siltation, lowered pH, and exposure to toxic coal ash elements. Coutant et al. (1978) identified seepage of water through ash deposits and containment dikes at the Bull Run Steam Plant (TVA) as a significant hazard to biota in the Clinch River. As a result of their assessment, the authors note containment banks were later enlarged to eliminate the ditch flow area. Efficient primary and secondary retaining basin design are viewed as imperative to prevent serious environmental contamination (Coutant et al. 1978). Accidental release of large quantities of ponded fly ash following breakdown of dike walls or basin overflow has proven catastrophic to aquatic biota. In one such case, invertebrates were eliminated from a 5 to 6 km stretch of the Clinch River and thousands of fish were killed when a caustic slug of coal ash was released following failure of a dike surrounding a fly ash retaining pond (Crossman et al. 1974).

Coal ash wastes have been identified as potentially hazardous pollutants due to their high suspended solids load, toxic element concentrations and extremely acid or alkaline nature. The impacts on the aquatic ecosystems to which they are discharged can be considerable. While this study and those of Cherry et al. (1979) and Crossman et al. (1974) demonstrate a relatively rapid recovery from a severely stressed condition, loss of sensitive species and sublethal stress may be inevitable at any exposure level.

REFERENCES

American Public Health Association. 1976. Standard methods for examination of water and wastewater. 14th Ed. Washington, D.C. 1193 p.

Andren, A., M. Anderson, N. Loux, and R. Talbot. 1977. Aquatic chemistry. p. 9-35. In: Documentation of environmental change related to the Columbia Electric Generating Station. Eleventh Semi-Annual Report. Report 92. Institute for Environmental Studies, University of Wisconsin-Madion.

Andrews, C. B., and M. P. Anderson. 1978. Impact of a power plant on the groundwtaer system of a wetland. Ground Water 16:105-111.

Aston, R. J., and A. G. P. Milner. 1980. A comparison of populations of the isopod *Asellus aquaticus* above and below power stations in organically polluted reaches of the River Trent. Freshwater Biol. 10:1-14.

Box, G. E. P., W. G. Hunter, and J. S. Hunter. 1978. Statistics for experimenters. John Wiley and Sons, Inc., New York. 653 p.

Cairns, J., Jr., K. L. Dickson, and G. Lanza. 1973. Rapid biological monitoring system for determining aquatic community structure in receiving streams. pp. 148-163. In: J. Cairns, Jr. and K. L. Dickson (eds.) Biological methods for the assessment of water quality. ASTM STP 528. Amercian Society for Testing and Materials, Philadelphia, Pennsylvania.

Cherry, D. S., S. R. Larrick, R. K. Guthrie, E. M. Davis, and F. F. Sherberger. 1979. Recovery of invertebrate and vertebrate populations in a coal ash stressed drainage system. J. Fish. Res. Bd. Can. 36:1089-1096.

Corkum, L. D., P. J. Pointing, and J. J. H. Ciborowski. 1977. The influence of current velocity and substrate on the distribution and drift of two species of mayflies (Ephemeroptera). Can. J. Zool. 55:1970-1977.

Coutant, C. C. 1964. Insecticide Sevin: Effect of aerial spraying on drift of stream insects. Science 146:420-421.

Coutant, C. C., C. S. Wasserman, M. S. Chung, D. B. Rubin, and M. Manning. 1978. Chemistry and biological hazard of a coal ash seepage stream. J. Water Pollut. Control Fed. 50:747-753.

Cover, E. C., and R. C. Harrel. 1978. Sequences of colonization diversity, biomass, and productivity of macroinvertebrates on artificial substrates in a freshwater canal. Hydrobiologia 59:81-95.

Crossman, J. S., R. L. Kaesler, and J. Cairns, Jr. 1974. The use of cluster analysis in the assessment of spills of hazardous materials. Am. Midl. Nat. 92:94-114.

Cummins, K. W. 1966. A review and future problems in benthic ecology. pp. 2-51. In: Organism-substrate relationships in streams. Special Pub. No. 4 Pymatuning Laboratory of Ecology, University of Pittsburgh.

Cummins, K. W., and G. H. Lauff. 1969. The influence of substrate particle size on the microdistribution of stream macrobenthos. Hydrobiologia 34:145-181.

Draper, N. R., and H. Smith. 1966. Applied regression analysis. John Wiley and Sons, New York. 407 p.

Elliot, J. M. 1977. Some methods for the statistical analysis of samples of benthic invertebrates. Freshwater Biological Association Scientific Publication No. 25. 160 p.

Forbes, A. M., and J. J. Magnuson. 1980. Decomposition and microbial colonization of leaves in a stream modified by coal ash effluent. Hydrobiologia 76:263-267.

Forbes, A. M., J. J. Magnuson, and D. M. Harrell. 1981. Effects of habitat modifications from coal ash effluents on stream macroinvertebrates. p. 241-249. In: L. A. Krumholz (ed.) Warmwater Streams Symposium. American Fisheries Society, Washington, D.C.

Fraser, J. 1980. Acclimation to lead in the freshwater isopod *Asellus aquaticus*. Oecologia (Berl.) 45:419-420.

Gee, J. H., and V. G. Bartnik. 1969. Simple stream tank simulating a rapids environment. J. Fish. Res. Bd. Can. 26:2227-2230.

Godfrey, P. J. 1978. Diversity as a measure of benthic macroinvertebrate community response to water pollution. Hydrobiologia 57:111-122.

Guthrie, R. K., E. M. Davis, D. S. Cherry, and J. R. Walton. 1982. Impact of coal ash from electric power production on changes in water quality. Water Res. Bull. 19:135-138.

Hall, R. J., G. E. Likens, S. B. Fiance, and G. R. Hendrey. 1980. Experimental acidification of a stream in the Hubbard Brook Experimental Forest, New Hampshire. Ecology 61:976-989.

Harrell, D. M. 1978. Effects on crayfish of exposure to coal ash effluent and to chromium contaminated food. M.S. Thesis. University of Wisconsin-Madison. Madison, Wisconsin. 134 pp.

Helmke, P. A., E. M. Larsen, W. P. Robarge, R. D. Koons, and J. Thresher. 1976a. Trace elements. p. 13-27. In: Documentation of environmental change related to the Columbia Electric Generating Station. Seventh Semi-Annual Report. Institute for Enviornmental Studies, University of Wisconsin-Madison.

Helmke, P. A., E. M. Larsen, W. P. Robarge, R. D. Koons, J. Thresher, and M. Schoenfield. 1976b. Trace elements. p. 152-160. In: Documentation of environmental change related to the Columbia Electric Generating Station. Eighth Semi-Annual Report. Institute for Environmental Studies, University of Wisconsin-Madison.

Hester, F. E. and J. S. Dendy. 1962. A multiple-plate sampler for aquatic macroinvertebrates. Trans. Am. Fish. Soc. 91:420-421.

Hilsenhoff, W. L. 1975. Aquatic insects of Wisconsin. Tech. Bull. 89. Wisconsin Department of Natural Resources, Madison, Wisconsin. 52 p.

Hilsenhoff, W. L. 1982. Using a biotic index to evaluate water quality in streams. Tech. Bull. 132. Wisconsin Department of Natural Resources, Madison, Wisconsin. 22 p.

Hocutt, C. H. 1975. Assessment of a stressed macroinvertebrate community. Water Res. Bull. 11:820-835.

Hynes, H. B. N. 1970. The ecology of running waters. University of Toronto Press, Toronto. 555 p.

Lehmkuhl, D. M. 1979. Environmental disturbance and life histories: principles and examples. J. Fish. Res. Bd. Can. 36:329-334.

Maciorowski, H. D., R. McV. Clarke, and E. Scherer. 1977. The use of avoidance-preference bioassays with aquatic invertebrates. Proc. 3rd Aquatic Toxicity Workshop, Halifax, N.S. Rept. No. EPS-5AR-77-1. Enviornmental Protection Services, Halifax, Canada. p. 49-58.

Maciorowski, A. F., E. F. Benfield, and J. Cairns, Jr. 1980. Preference-avoidance reactions of crayfish to sublethal concentrations of cadmium. Hydrobiologia 74:105-112.

Magnuson, J. J., A. M. Forbes, D. M. Harrell, and J. D. Schwarzmeier. 1980a. Responses of stream invertebrates to an ash pit effluent. Wisconsin Power Plant Impact Study. EPA-600/3-80-081. U.S. Environmental Protection Agency. Cincinnati, Ohio.

Magnuson, J. J., F. J. Rahel, M. J. Talbot, A. M. Forbes, and P. A. Medvick. 1980b. Ecological studies of fish near a coal-fired electric generating station and related laboratory studies. Wisconsin Power Plant Impact Study. EPA-600/3-80-078. U.S. Environmental Protection Agency, Cincinnati, Ohio.

Mason, W. T., J. B. Anderson, R. D. Kreis, and W. C. Johnson. 1970. Artificial substrate sampling, macroinvertebrates in a polluted reach of the Klamath River, Oregon. J. Water Pollut. Control Fed. 2:315-328.

Mason, W. T., C. I. Weber, P. A. Lewis, and E. C. Julian. 1973. Factors affecting the performance of basket and mulitplate macroinvertebrate samplers. Freshwater Biol. 3:409-436.

Merritt, R. W., and K. W. Cummins. 1978. An introduction to the aquatic insects of North America. Kendall/Hunt Publishing Co., Dubuque, Iowa. 441 p.

Newell, R. C. 1973. Factors affecting the respiration of intertidal invertebrates. Am. Zool. 13:513-528.

Otto, C. 1976. Factors affecting the drift of *Potamophylax cingulatus* (Trichoptera) larvae. Oikos 27:93-100.

Pennak, R. W. 1978. Freshwater invertebrates of the United States. 2nd Ed. John Wiley and Sons, New York. 803 p.

Pielou, E. C. 1969. An introduction to mathematical ecology. Wiley-Interscience, New York. 286 p.

Roback, S. S. 1974. Insects (Arthropoda:Insecta). p. 315-376. In: C. W. Hart and S. L. H. Fuller (eds.) Pollution ecology of freshwater invertebrates. Academic Press, New York. 387 p.

Rosenberg, D. M., and A. P. Wiens. 1978. Effects of sediment addition on macrobenthic invertebrates in a northern Canadian River. Water Res. 12:753-763.

Roy, W. R., R. G. Thiery, R. M. Schuller, and J. J. Suloway. 1981. Coal fly ash: A review of the literature and proposed classification system with emphasis on environmental impacts. Environ. Geol. Notes 96. Illinois Institute of Natural Resources, Chicago, Illinois. 69 p.

Ruggiero, M. A., and H. C. Merchant. 1979. Water quality, substrate, and distribution of macroinvertebrates in the Patuxent River, Maryland. Hydrobiologia 64:183-189.

Scherer, E. 1977. Behavioral assays - principles, results and problems. Proc. 3rd Aquatic Toxicity Workshop, Halifax, N. S., Tech. Rept. No. EPS-5AT-77-1. Environmental Protection Service. Halifax, Canada. p. 33-40.

Siegel, S. 1956. Nonparametric statistics for the behavioral sciences. McGraw-Hill, New York. 312 p.

Soholt, L. F., N. J. Beskid, W. J. Derikson, M. J. Knight, D. D. Ness, B. Siskind, and W. S. White. 1980. Handling of combustion and emission-abatement wastes for coal-fired power plants: Implications for fish and wildlife resources. FWS/OBS-80/33. Washington, D.C. U.S. Fish and Wildlife Service. 184 p.

U.S. Environmental Protection Agency. 1976. Quality criteria for water. U.S. Environmental Protection Agency, Washington, D.C. 256 p.

Walton, O. E. 1978. Substrate attachment by drifting aquatic insect larvae. Ecology 59:1023-1030.

Waters, T. F. 1972. The drift of stream insects. Ann. Rev. Entomol. 17:253-272.

Weber, C. I. 1973. Biological field and laboratory methods for measuring the quality of surface waters and effluents. Environmental monitoring series. EPA-670/4-73-001. U.S. Environmental Protection Agency, Cincinnati, Ohio. 125 p.

Webster, K. E., A. M. Forbes, and J. J. Magnuson. 1981. Behavioral responses of stream macroinvertebrates to habitat modification by a coal ash effluent. p. 408-414. In: L. A. Krumholz (ed.) Warmwater Streams Symposium. American Fisheries Society, Washington, D.C.

Wentsel, R., A. McIntosh, W. P. McCafferty, G. Atchison, and V. Anderson. 1977a. Avoidance response of midge larvae (*Chironomus tetans*) to sediments containing heavy metals). Hydrobiologia 55:171-175.

Wentsel, R., A. McIntosh, and G. Atchison. 1977b. Sublethal effects of heavy metal contaminated sediment on midge larvae (*Chironomus tetans*). Hydrobiologia 56:153-156.

Wilhm, J. L., and T. C. Dorris. 1968. Biological parameters for water quality criteria. Bioscience 18:477-481.

Winner, R. W., and M. P. Farrell. 1976. Acute and chronic toxicity of copper to four species of *Daphnia*. J. Fish. Res. Bd. Can. 33:1685-1691.